# AN ALTERNATE APPROACH TO DETERMINE THE EXPLOSIBLITY OF DUSTS

A Dissertation

by

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# ABSTRACT

A dust is classified as explosible based on the laboratory tests specified by the American Society for Testing and Materials (ASTM) E 1226. This standard requires that a dust be uniformly dispersed into an enclosed 20-Liter (L) chamber forming a dust cloud; a 10,000 Joule (10 kJ) flame is subsequently forced through the dust cloud and the resulting pressure rise is measured. If the pressure rise exceeds one bar (14.5 psig), it is assumed that a deflagration occurred, and the dust is classified as class „A‟ explosible dust. We have reported several flaws in the current ASTM testing protocols. The only indicator used by the ASTM method for assuming a deflagration had occurred in the test chamber is pressure rise. CAAQES has developed an alternative protocol that more accurately characterizes the explosibility of dusts. The CAAQES protocol for determining MEC is to test a wide range of concentrations of a dust in a 28.3-L (1 $ft^3$) Plexiglas chamber with a diaphragm and a stationary ignition source. If a self-propagating flame results as indicated by the diaphragm bursting, the Pressure vs. Time curve, and the flame leaving the chamber, a deflagration occurred during the test and the dust is explosible.

Several dusts were tested along with cotton gin dust (CGD) for explosibility. The CGD does not have a MEC and hence it is non-explosible, contrary to the results reported by the Safety Consulting Engineers Inc. (SEC Inc.). The SCE Inc. tested CGD for explosibility based on the ASTM E1226 standard and reported CGD as class „A‟ explosible dust. The difference in test results triggered a research on characterizing a dust for explosibility by the CAAQES. The MECs of dusts were reported and compared with the MECs determined by Palmer in 1973 and the U.S. Bureau of Mines in1964. Further studies were also conducted to determine the dust properties affecting the explosibility of a dust. The CGD consisted of 87% inerts with a low energy content of 1400 J g$^{-1}$. The properties of CGD rendered it non-explosible. Dusts were mixed with Fuller‟s earth and tested in the CAAQES chamber in order to study the effect of inert mass fraction of a dust on MECs. It was hypothesized that, at a specific concentration, the distance between the combustible particles must be at a certain distance to enable a flame to propagate from one particle to another. The distance between the combustible particles should be 450 to 700 μm to propagate the flame from one particle to another in the CAAQES chamber. Approximately, 50% of inerts (Fuller‟s earth) prevented a deflagration for all dusts. The energy content of agricultural dusts should be above 7000 J g$^{-1}$ to result in a deflagration.  It was also concluded that the dust properties influences the explosibility of a dust.

# DEDICATION

To my Mom and Dad.

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# NOMENCLATURE

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| C | Carbon |
| $CO_2$ | Carbon dioxide |
| $C_v$ | Specific heat at constant volume |
| $d_s$ | Imaginary sphere diameter |
| $d_p$ | Particle diameter |
| $\Delta u$ | Change in internal energy |
| $\Delta T$ | Change in Temperature |
| CAAQES | Center for Agricultural Air Quality Engineering and Science |
| CGD | Cotton gin dust |
| $\rho$ | Density |
| $K_{st}$ | Deflagration Index |
| MW | Molecular weight |
| MEC | Minimum explosible concentration |
| N | Number of particles |
| $N_2$ | Nitrogen |
| NCGA | National Cotton Ginners Association |
| NEP | National Emphasis Program |
| $O_2$ | Oxygen |
| OSHA | Occupational Safety and Health Administration |

|  |  |
|---|---|
| P | Pressure |
| R | Universal gas constant |
| SCE | Safety Consulting Engineers |
| STP | Standard Temperature and Pressure |
| T | Time |
| V | Volume |
| $V_p$ | Particle volume |
| $P_d$ | Particle density |

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# CHAPTER I

# INTRODUCTION AND LITERATURE REVIEW

## Introduction

Dusts explosions are a serious threat to industries handling flammable dust. The U.S. Chemical Safety Board reported 281 major dust explosion incidents, which killed 119 workers and injured 718 more, from 1989 to 2005 (CSB, 2006). Primarily the dust explosions are common in flour milling, grain storage, and coal mining (Sam Mannan, 2005). A dust explosion is a rapid burning of a dust cloud resulting in a pressure rise, which ruptures the initial containment. Dust explosions are deflagrations, in which the reaction wave propagates at a speed less than the speed of sound. For a deflagration to occur, the dust must be entrained in air at a concentration at or above the minimum explosible concentration (MEC) in the presence of oxygen, ignition source, and containment. A dust explosion is a series of incidents; the initial explosion is referred as the primary explosion and the multiple explosions that occur after the primary are referred as secondary explosions. A primary explosion occurs with a pressure of less than 2 psig. The secondary explosions results in a pressure greater than 150 psig (Palmer, 1973). A primary explosion occurs in a process unit releasing the pressure wave and a flame front, which travel at a speed of sound (330 m $s^{-1}$) and at a speed of 2-10 m $s^{-1}$, respectively. The secondary explosions are initiated due to the entrainment of a dust layer in air by the pressure wave originating from a primary explosion and the flame front serving as an ignition source. The unburned dust remaining after a primary explosion may also be carried by the pressure wave to a secondary area, serving as an additional fuel for secondary explosions. The secondary explosions are often more severe than the primary explosion resulting in potential damages (Lesikar et al., 1991).

According to Palmer (1973) not all combustible dusts are explosible, but all explosible dusts are combustible. For a dust to be explosible, it must have a MEC, which is the lowest concentration that results in a self-propagating flame through the dust cloud (Nomura and Tanaka, 1992). The flame self-propagates only if the dust concentration exceeds the MEC. Dusts are classified as explosible based upon laboratory tests. Palmer (1973) classified dusts as Group (a) if they are ignited and propagate the flame through the dust cloud, and Group (b) if they do not propagate the flame through the dust cloud (non-explosible). The explosibility of a dust was determined using a 1.2-L vertical Hartmann tube with an ignition energy of 10 J by the U.S Bureau of Mines and Palmer (1973). If a flame propagates beyond the ignitor, the dust was explosible (Nagy and Verakis, 1964). Bartknecht (1971) developed an explosion chamber of 1 $m^3$ volume to determine the explosibility of dusts. A strong pyrotechnic igniter of 10 kJ was used to ignite the dust cloud. The 1 $m^3$ chamber replaced the 1.2-L Hartmann tube as a standard explosible dust testing chamber due to wall effects, in which the walls suppress the flame prematurely. Bartknecht (1981) and Field (1982) developed a 20-L spherical explosion chamber in which a test dust is injected with air, forming a dust cloud. Subsequently, a flame from a 10 kJ pyrotechnic igniter is forced through the dust cloud, and the resulting pressure rise is recorded. If the pressure rise exceeds 1 bar, the dust is classified as explosible. Parnell et al. (2013) reported several flaws in the current ASTM standard testing procedures. CAAQES personnel developed an alternative explosible dust testing method using a 1 ft$^3$ (28.2-L) Plexiglass chamber with a diaphragm and a stationary ignition source. According to the CAAQES protocol, a dust is classified as explosible based on the existence of a MEC. If a MEC does not exist, the dust is non-explosible. The CAAQES protocol uses three indicators to determine the MEC of a dust; the diaphragm must rupture due to the pressure rise, the self-propagating flame must leave the chamber, and a characteristic Pressure vs. Time curve is obtained.

CAAQES was requested to test cotton gin dust (CGD) for explosibility by the National Cotton Ginners Association (NCGA). CGD was tested for different concentrations using the CAAQES chamber. No deflagrations were observed for any of the concentrations tested. The CAAQES reported CGD was non-explosible as it does not have a MEC. The Safety Consulting Engineers Inc. tested CGD for explosibility based on the ASTM standard and reported CGD was a class „A‟ explosible dust. CAAQES personnel conducted a thorough study on test methods to characterize the explosibility of a dust and the findings are reported in this dissertation.

## Literature review

Cashdollar and Chatrathi (1993) used a 20-L and 1-m$^3$ spherical chambers to determine the MECs for gilsonite and bituminous coal dust with different ignition energies ranging from 500 J to 10 kJ. It was concluded that the 20-L chamber results were “over-driven” at high ignition energies. The MECs measured in a 20-L chamber using a 2.5 kJ ignition energy was comparable to the 1 m$^3$ chamber with the ignition energy of 10 kJ. Due to the "over-driven" results, a dust is mislabeled as explosible in a 20-L chamber. The only alternative for an "over-driven" result is the dust must be tested in a 1 $m^3$ chamber (ASTM E1226-05).

Gibson et al. (1986) reported that the high ignition energy decomposes the dust prior to the ignition, and the gas evolved resulted in an explosion contributing to the pressure rise in the 20-L chamber. The energy source of 10 kJ is rarely, if ever, present in dust handling facilities. The data obtained with this high ignition source, which is not available in a facility, must be validated.

Proust et al. (2007) reported that there were significant discrepancies in the test results between the 1 $m^3$ and 20-L chamber. The dusts, which were explosible in the 20-L sphere, were non-explosible in the 1 $m^3$ chamber. This is due to the "preheating" caused by the strong igniters in the 20-L chamber, which increases the temperature, and subsequently the combustion reaction is overdriven, yielding false-positive results.

Myers (2008) reported that results, obtained using a 20-L chamber, were consistent with the 1 $m^3$ chamber for dusts with greater explosion severity. The dust with lower $K_{st}$ values yielded "over-driven" results. The deflagration index ($K_{st}$) is used to estimate the rate of maximum pressure rise in a 1 $m^3$ chamber with respect to the 20-L chamber using the cube-root law. The pressure rise recorded in an "over-driven" test was due to the burning of a dust at the igniter rather than the self-propagation of a flame through the dust cloud.

Dahoe et al. (1996) reported the limitations of the cube-root law which is used to estimate the maximum rate of pressure rise in a 1 $m^3$ chamber from a 20-L sphere. The inaccuracy of the cube-root law leads to the improper design of explosion venting.

For a dust to be explosible, it must have a MEC (Palmer, 1973). The flame self-propagates through the dust cloud only if the dust concentration is at or above the MEC. Palmer and Butlin (1972) reported that the test chamber design must ensure that the flame self-propagates through the dust cloud if the concentration exceeds the MEC. In a 20-L chamber, it is not evident that the flame self-propagates from the center of the sphere through the dust cloud (Snoeys et al., 2006).

## Objectives

The goal of this research was to determine if cotton gin dust was explosible with specific objectives as follows:

(1) Document the flaws in the current ASTM explosible dust testing procedures.

(2) Establish an alternative CAAQES explosible dust testing method and determine the MECs of organic dusts.

(3) Demonstrate the impact of inert mass fraction on explosible dusts.

# CHAPTER II

# PROBLEMS IN THE ASTM STANDARD EXPLOSIBLE DUST TESTING PROCEDURE*

## Introduction

The sugar dust explosion on February 7, 2008 at the Imperial Sugar Company Plant in Savannah, GA killed 14 people and injured 38 (CSB, 2009). After this explosion, the Occupational Safety and Health Administration (OSHA) initiated the combustible dust National Emphasis Program (NEP) to improve its enforcement activities on facilities handling dusts. According to the NEP, all the dust handling facilities, excluding grain handling facilities, must test the dusts for explosibility (OSHA, 2008). A comprehensive survey was conducted by the OSHA to identify all possible explosible dusts that could serve as a fuel for explosions. Most of the data were collected based upon the fire marshal‟s reports and past incidents. According to the survey, OSHA reported that dust from ginning operations have fuelled dust explosions in the past. It is likely that periodic fires in cotton gins could have been incorrectly reported as explosions. The National Cotton Ginners Association (NCGA) requested the CAAQES to test the cotton gin dust (CGD) for explosibility. CAAQES personnel conducted several tests on CGD and reported that CGD was non-explosible. Subsequent to Parnell et al. (2013) reporting of the CAAQES testing results to the NCGA, the

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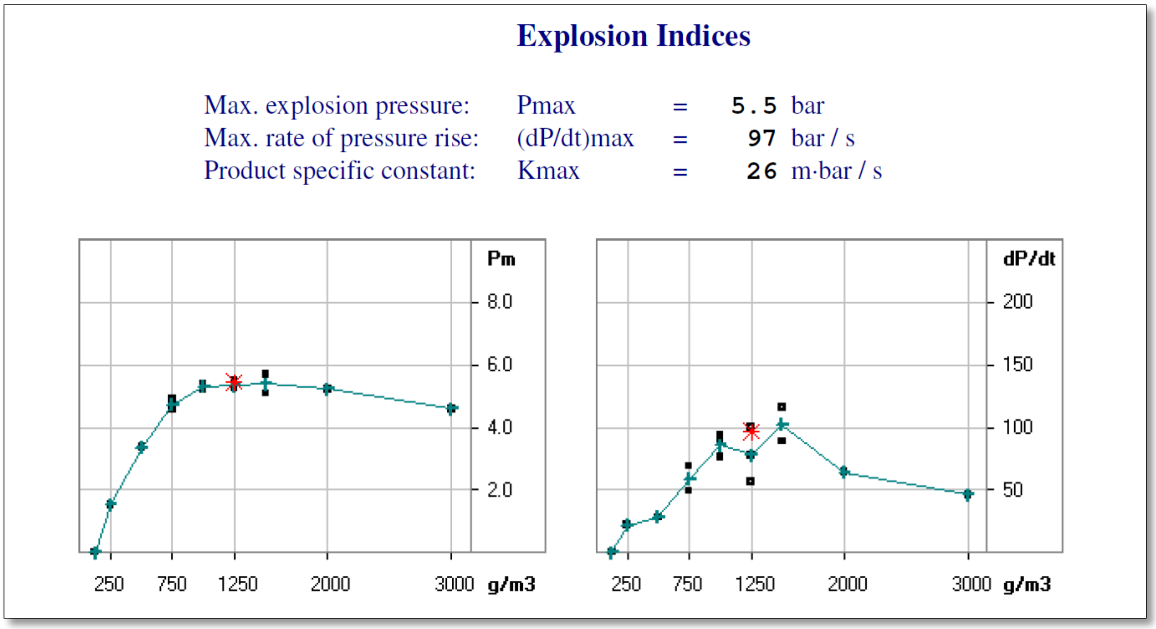
* Part of this chapter is reprinted with permission from "A critical evaluation of combustible/explosible dust testing methods-Part 1" Parnell Jr., C. B., R.O. McGee, B. Ganesan, F.J. Vanderlick, S.E. Hughs and K Green. 2013. *Journal of Loss Prevention in the Process Industries,* 26, 427-433. Copyright 2013 Elsevier.

NCGA requested that CGD be tested in a commercial laboratory based on the ASTM standard testing procedure. The same CGD samples were forwarded to Safety Consulting Engineers Inc. (SCE) for testing. The SCE conducted a screening test using a 1.2-L Hartmann tube, and tested CGD for 10 replications of 11 different concentrations. The CGD was tested up to a concentration of 16,600 g $m^{-3}$, and no deflagrations were observed for any of the concentrations tested. Further testings were conducted using a 20-L spherical chamber recommended by the ASTM standard with a strong ignition source of 10 kJ. The SCE reported CGD was a class „A" explosible dust based on the ASTM method. The results of a single test for a concentration of 1000 g $m^{-3}$ are shown in Table 1. The criterion used by the SCE for a deflagration to occur with respect to the explosibility classification was 0.4 bar (g), and the criterion for determining the MEC was 0.5 bar (g). The ASTM threshold is listed as 1 bar (g) (ASTM E1515-07, 2007). The maximum pressure was reported as 5.6 bar (abs) at a concentration of 1,000 g/$m^3$ (SCE, 2010). Subsequently a series of tests were conducted by SCE, and the results are shown in Figure 1 and Table 2.

**Table 1.** Test results of CGD in the 20-L chamber with a 10 kJ ignition source. The ignition criterion was a max pressure ≥ 0.4 bar.

| Test No. | Dust Cloud Concentration (g/$m^3$) | Explosion Pressure (bar) | Rate of pressure rise dP/dt (bar/s) | Ignition |
|---|---|---|---|---|
| 1 | 1000 | 5.6 | 79 | Yes |



Explosion Indices

Max. explosion pressure: Pmax = 5.5 bar
Max. rate of pressure rise: (dP/dt)max = 97 bar / s
Product specific constant: Kmax = 26 m·bar / s

**Figure 1.** Concentration vs. pressure and concentration vs. rate of pressure rise curve for CGD in a 20-L chamber.

**Table 2.** The ASTM 20-L chamber results for a series of tests conducted on CGD by SCE (Note: The bolded values are the maximum pressure rise and rate of pressure rise in each series).

| (Series) Test | Dust Cloud Concentration ($g/m^3$) | Explosion Pressure (bar) | Rate of pressure rise dP/dt (bar/s) |
|---|---|---|---|
| (1) 1 | 125 | 0.0 | 0 |
| (1) 2 | 250 | 1.5 | 22 |
| (1) 3 | 500 | 3.4 | 28 |
| (1) 4 | 750 | 4.9 | 49 |
| (1) 5 | 1000 | 5.3 | 94 |

**Table 2**. continued

| (Series) Test | Dust Cloud Concentration (g/m$^3$) | Explosion Pressure (bar) | Rate of pressure rise dP/dt (bar/s) |
|---|---|---|---|
| (1) 6 | 1250 | 5.5 | 78 |
| (1) 7 | **1500** | **5.7** | **116** |
| (1) 8 | 2000 | 5.2 | 64 |
| (1) 9 | 3000 | 4.6 | 46 |
| (2) 10 | **1250** | **5.3** | **100** |
| (2) 11 | 1500 | 5.1 | 89 |
| (2) 12 | 1000 | 5.2 | 88 |
| (3) 13 | **1000** | **5.4** | **76** |
| (3) 14 | 1250 | 5.2 | 56 |
| (3) 15 | 750 | 4.6 | 69 |

The rates of pressure rise reported by the SCE were inconsistent. For the concentration of 1250 g m$^{-3}$, the rate of pressure rise recorded in each series was significantly different. The rates of pressure rise recorded varied from 20 to 45% for the same concentration tested in the 20-L chamber. The rate of pressure rise recorded in a 20-L chamber was different for each replication. The failure to reproduce a consistent rate of pressure rise for each replication will yield in improper design of explosion venting.

Figure 2a

Figure 2b

Figure 2c

**Figure 2.** Different explosible dust testing chambers

Figure 2 shows the explosion chambers used to classify a dust. Figure 2a is the enclosed Hartmann used in the screening tests by SCE. The enclosed Hartmann had a continuous arc ignition source with energy of 10 kJ. A dust sample is classified as explosible if a flame propagates beyond the ignition source. Figure 2b shows a deflagration in the 1.2-L Hartmann tube with a diaphragm, which was the protocol used by Palmer (1973) and U.S. Bureau of Mines. Figure 2c shows the 20-L chamber specified by the ASTM E1226 standard. It is a totally enclosed chamber used to determine maximum rate of pressure rise, and maximum pressure as specified by ASTM E1226 and MEC as specified by ASTM E1515.

## Objective

The objective of this section is to document the flaws in the current ASTM explosible dust testing protocols. The specific objectives are as follows:

(a) Estimate the available oxygen for combustion.

(b) Determine the theoretical pressure rise in the ASTM chamber.

(c) Demonstrate that using a high ignition energy influence the characterization of a dust.

## The ASTM explosible testing method

The current ASTM standard recommends a 20-L chamber to test a dust for explosibility. A dust is injected into the chamber with compressed air forming a dust cloud. Subsequently, a moving flame is forced through the dust cloud after a specific ignition delay time, and the rise in pressure is recorded. If the pressure rise exceeds 1 bar, the dust is classified as explosible. The only indicator used for assuming a deflagration had occurred in the ASTM chamber is pressure rise. The problems in the ASTM testing procedures are as follows:

(1) For a dust to be explosible, it must have a MEC (Palmer, 1973). If a dust does not have a MEC, a flame will not self-propagate through the dust cloud, and will not result in a dust explosion (Nomura and Tanaka, 1992). Parnell (1978) described that for a primary explosion to occur, MEC must exist. In order for secondary explosions to occur, there must be a primary explosion. If the concentration is less than the MEC, no explosion will occur even in the presence of oxygen, containment, and an ignition source. *The ASTM method does not use MEC as a criterion to determine the explosibility of a dust*.

(2) A deflagration occurs due to the pressure rise produced by a self-propagating flame through the dust cloud. Forcing a flame through the dust cloud that is 1,000 times higher than the 10 J used by Palmer and U.S. Bureau of Mines will not result in a self-propagating flame. It is likely that the combustion of dust in the chamber will result in a pressure exceeding one bar without a self-propagating flame. The explosible dust testing protocol must ensure the self-propagation of a flame, and in the ASTM method, it is not obvious that the flame is self-propagating through the dust cloud (Snoeys et al., 2006).

(3) Parnell et al. (2013) reported that a 20-L chamber contains only 5.5 g of oxygen. The ASTM chamber is oxygen-limited. A complete combustion of 2 g of dust will consume all the oxygen in the chamber. Tests were conducted up to a concentration of 3000 g $m^{-3}$ in the ASTM chamber, which does not have sufficient oxygen for combustion.

(4) Cashdollar and Chatrathi (1993) describe the result of classifying dusts as explosible when they are not explosible as a consequence of using the 10 kJ ignition source. These results are referred as “over-driven” results. The only option for “over-driven” results is to test the dusts in a one cubic meter chamber (ASTM E1226-05, 2005). The “over-driven” results are due to dusts burning at the ignitor and increasing the pressure rather than a deflagration.

## Engineering calculations

The available oxygen and theoretical pressure rise was determined using the ideal gas law and specific heat at constant volume equations. The following assumptions were made: (1) the reaction is adiabatic, that is, no heat losses to the surrounding (2) complete combustion of 1 g of carbon, a surrogate for a test dust. The following combustion reaction is hypothesized as the reaction of carbon burning, representing the combustible dust in the 20-L chamber:

$$C + O_2 + 3.76N_2 \rightarrow CO_2 + 3.76N_2 \tag{1}$$

### *Estimating available oxygen in the 20-L chamber*

The molecular weight of the gas prior to the reaction consisting of one mole of oxygen and 3.76 moles of nitrogen at STP is 28.8. Using the molecular weights of oxygen (MW=32) and nitrogen (MW=28), the molecular weight of gas prior to the reaction is determined using the Equation (2)

$$MW = \frac{32 + 3.76 * 28}{4.76} = 28.8 \tag{2}$$

The density of gas prior to the reaction is given by Equation (3).

$$\rho = \frac{P \times MW}{R \times T} = \frac{1atm \times 29}{0.08206 \times (273 + 25)} = 1.19g / L \tag{3}$$

The mass of air in the 20-L chamber prior to the reaction is 23.8 g (1.19 g $L^{-1}$ * 20 L). The mass of oxygen ($M_{oxy}$) available for the reaction is

$$M_{oxy} = (\frac{32}{32+105.28})*23.8 = 5.5g \tag{4}$$

One gram of carbon (0.0833 moles) will consume 2.67 g of $O_2$ (0.0833 moles) in a stoichiometric reaction. For this scenario, all the oxygen will be consumed by 2 g of carbon.

### *Estimating the pressure rise in the 20-L chamber*

The MW of gas and mass of gas produced after the complete combustion of one gram carbon is 31.4 and 24.8, respectively. The specific heat at constant volume ($C_v$) is defined as the ratio of the change in internal energy (Δu) per unit mass required to increase gas temperature by one degree kelvin (ΔT).

$$C_v = \frac{\Delta u}{\Delta T} \tag{5}$$

where,

$C_v$ = 0.95 J/ (g-deg K)

The $C_v$ of the gases produced was used to determine the temperature rise. The energy content of carbon is 32,000 J $g^{-1}$. To be conservative, we used the energy content of carbon as 16,000 J $g^{-1}$ to estimate the rise in temperature. The energy contents of different organic dusts were determined using a bomb calorimeter. The heating values of different organic dusts ranged from 15,500 and 16,500 J $g^{-1}$. The test results also signified that the energy content used for the calculations was reasonable. The test that SCE was required to use before gin dust could be classified as “non-explosible” was to test 1,000 g $m^{-3}$ with an ignition flame from a 10 kJ energy source. The total energy in the chamber would be 26 kJ. The energy per unit of mass $\Delta u$ = 26 kJ/24.8= 1050 J/g. The temperature rise (Eq 5) would be 1050/0.95=1100 deg. K The absolute temperature would be 1400 deg K. Using the ideal gas law, the absolute pressure due to this rise in temperature would be 4.5 bar or a pressure rise of 3.5 bar (g). Table 3 shows the pressure that would result for one gram of combustible dust having energy of 16 kJ and ignition flames from 2.5, 5, and 10 kJ.

**Table 3.** Results of engineering calculations for different ignition and dust energies in the 20-L chamber

| Ignition Energy, kJ | Dust Energy, kJ | Temp (abs), Deg.K | Pressure, bar(abs) | Pressure, barg |
|---|---|---|---|---|
| 2.5 | 16 | 1080 | 3.5 | 2.5 |
| 5.0 | 16 | 1190 | 3.9 | 2.9 |
| 10 | 16 | 1400 | 4.5 | 3.5 |
| **10** | **0** | **722** | **2.4** | **1.4** |

Note that the flame from a 10 kJ ignition source without any dust in the chamber will result in a pressure rise that exceeds one bar. A dust is classified as explosible if the pressure rise exceeds 1 bar in a 20-L chamber according to the ASTM standards. It is likely to classify a non-explosible dust as explosible by using a strong ignition source, where the rise in pressure is not due to a deflagration but due to the igniter itself.

## Summary

Using pressure as the only indicator for assuming a deflagration had occurred in the ASTM chamber results in false positives. Several potential problems in the ASTM standard testing procedures were reported based on our research. A dust must have a MEC to result in a deflagration. A dust must be classified based upon the CAAQES protocols or similar protocols proposed by Palmer and U.S. Bureau of Mines. The ASTM method classifies a non-explosible dust as explosible as the results are „over-driven‟. The inaccurate results obtained from the ASTM method will force the industries handling mislabeled dusts to install unnecessary additional control system at a huge cost. The specific problems with the ASTM protocols are as follows:

1. The ASTM method does not use MEC as a criterion to classify a dust. Using pressure as the only indicator for deflagration will yield inaccurate results.
2. Forcing a flame from a 10 kJ igniter through the dust cloud will not results in a self-propagating flame. It is not evident that the flame self-propagates through the cloud, if the dust concentration exceeds the MEC.

3. Using strong igniters will overdrive the test results leading to classify a dust as explosible when it is not.
4. The ASTM chamber is oxygen-limited. It contains only 5.5 g of oxygen and 2 g of dust will consume all of it.

# CHAPTER III

# AN ALTERNATE EXPLOSIBLE DUST TEST PROTOCOL: CAAQES METHOD[*]

## Introduction

Dust explosions are a series of incidents. The first initial explosion is referred as primary explosion and the subsequent multiple explosions are secondary explosions. Secondary dust explosions cannot occur unless there is a primary. Primary explosions cannot occur unless there is a minimum explosible concentration (MEC). A dust explosion will not occur if the dust concentration is lower than the MEC even at the presence of oxygen, ignition source, and containment. The concept of Center for Agricultural Air Quality and Science (CAAQES) method was that a dust explosion can be prevented by preventing a primary dust explosion and secondary explosions do not occur without a primary explosion. A primary explosion occurs only if the dust concentration exceeds a MEC. A primary explosion results in a pressure wave leaving the ignition location that can entrain sufficient dust into the secondary chamber to propagate a secondary explosion (Lesikar et al, 1991). Lesikar et al. (1991) reported that there may be sufficient dust carried by the pressure wave to a secondary chamber to fuel a secondary dust explosion. *For a dust to be explosible, it must have a MEC.*

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[*] Part of this chapter is submitted for publication "A critical evaluation of explosible dust testing methods-Part II" Ganesan. B, C.B. Parnell Jr., R.O. McGee. 2013. *Combustion Science and Technology (in peer review)*

An alternative explosible testing methodology is proposed to characterize a dust for explosibility. The CAAQES method was developed based upon the explosible dust testing protocols described by Palmer (1973). The CAAQES chamber is a 28.3-L (1 ft$^3$) cube consisting of a stationary ignition source and a diaphragm. A solenoid valve with timers is used to disperse the dust with compressed air, and a pressure sensor is fitted in the chamber to record the Pressure vs. Time data. The CAAQES method exactly mimics a primary dust explosion in a grain handling facility. In a grain dust explosion, the dust concentration at or above the MEC is ignited by a stationary source, such as a hot bearing, resulting in a self-propagating flame rupturing the initial containment. A deflagration in the CAAQES chamber is similar to a dust explosion in a boot of a leg ignited by a hot bearing. In the CAAQES chamber, the dust cloud is ignited by a stationary heating coil resulting in a self-propagating flame. The pressure rise due to the self-propagating flame ruptures the diaphragm in the CAAQES chamber is similar to the rupturing of the initial containment in the grain elevator or feed mill. Figure 1 shows the explosion of corn starch in the CAAQES chamber at a concentration of 50 g m$^{-3}$. The ignition energy of the heating coil was determined by measuring the resistance and voltage across the coil using a Multimeter. The measured voltage and resistance of the heating coil was 93 Volts and 123 Ohms. According to the power law, the relationship between power, voltage and resistance is given by

$$P = \frac{V^2}{R} \tag{6}$$

The calculated power was 72 watts. The ignition energy of the coil after 1.5 minutes was 6500 J. The ignition energy was also estimated using the specific heat equation. The coil wire was made of Nichrome with a specific heat constant of 450 J kg$^{-1}$ $^{o}$C$^{-1}$. The mass of the coil was 27 g. The ignition temperature of the coil was set at 360$^{o}$C. Using the Equation 7, the estimated ignition energy of the coil was 4070 J.

$$C_v = \frac{\Delta u}{\Delta T} \tag{7}$$

where,

$C_v$ = specific heat constant of Nichrome, J Kg$^{-1}$ deg-C$^{-1}$

$\Delta$u = Change in internal energy, J g$^{-1}$

$\Delta$T = Change in Temperature, $^{o}$C

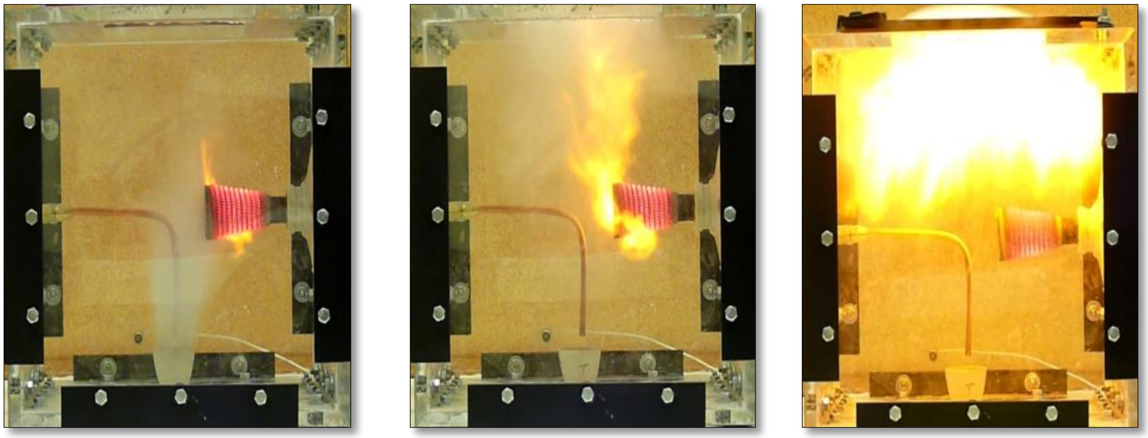

**Figure 3**. A deflagration fueled by corn starch in the CAAQES chamber at 50 g m$^{-3}$

Figure 3 is the frames taken from a video recorded while testing corn starch at a concentration of 50 g $m^{-3}$.Frame 1 (left) shows the dust being dispersed into a dust cloud at a concentration higher than the MEC of corn starch. In Frame 2 (center), the dust cloud touches the stationary hot coil that serves as the ignition source. Frame 3 (right) shows the flame self-propagating from the coil through the dust cloud. The resulting pressure is sufficient to burst the diaphragm and the flame leaves the chamber. Note: Unlike the ASTM chamber, the volume occupied by the dust cloud in the chamber of the MEC is only a fraction of the 28.3-L cubic CAAQES chamber.

The CAAQES protocol has the following improvements over the ASTM method for determining whether a dust is explosible:

1. Consistent with the criteria used by Palmer (1973), the criterion for a dust to be explosible with the CAAQES protocol is the existence of a MEC. If there is a deflagration for any test concentration in the CAAQES chamber, the dust is considered explosible.

2. The dust cloud is ignited by a stationary ignition source (hot coil) at a temperature sufficient to initiate a flame. The self-propagated flame produces a pressure sufficient to rupture the diaphragm (approximately 1-2 psig). According to Palmer (1973), the primary dust explosion generates a pressure wave that ruptures the containment with a pressure of approximately 2 psig. The deflagration releases a pressure wave followed by a fire front that enters another larger area and entrain layered dust into a secondary MEC. The speed of the

pressure wave is typically near the speed of sound (330 m sec$^{-1}$). The fire front follows at a speed of 2 to 10 m sec$^{-1}$ and can serve as the ignitor for secondary dust explosions, which can produce pressures of 150 psig (Lesikar et al., 1991).

3. The CAAQES methodology utilizes three indicators to determine whether a deflagration has occurred in the chamber:
    a. The diaphragm ruptures due to the pressure rise.
    b. A flame is observed leaving the CAAQES chamber and
    c. A characteristic Pressure vs. Time (PvT) curve is observed

The diaphragm (22 cm by 30 cm) was engineered to rupture if the pressure rise exceeded 2 psig. Numerous tests were conducted with different diaphragms with an opening of various sizes. Based on several tests, a diaphragm with a 1/8-inch opening at the center of the diaphragm was used for CAAQES testing. A characteristic PvT curve consists of (1) an initial rapid rise in pressure indicating that the dust cloud, at a concentration at or above the MEC, was burning as a consequence of a self-propagating flame ignited by the stationary coil; (2) this was followed by a rapid pressure decrease as a consequence of the ruptured diaphragm releasing the flame and gases; and finally, (3) a measured gage pressure below atmospheric pressure (vacuum) as a response to the rapid movement of gases from the chamber. The vacuum created in the CAAQES chamber was typical of an aftermath of a primary dust explosion. After a primary explosion, the pipes at the site collapse and create a vacuum. The same phenomenon was observed in the PvT curves. Figure 4 shows characteristic PvT curves for corn starch tested in the

CAAQES chamber at a concentration of 50 g m$^{-3}$. Three replications of the test are shown in Figure 4. A fraction of the volume of the chamber was used to determine the dust concentration. In the ASTM chamber, the dust is dispersed throughout the chamber to define the dust concentration. The dust cloud volume was determined to be approximately 10-L based on image analysis. The CAAQES method demonstrates that there is no need to disperse the dust in an entire chamber, and only a fraction of a volume of the chamber is sufficient for a deflagration to occur.

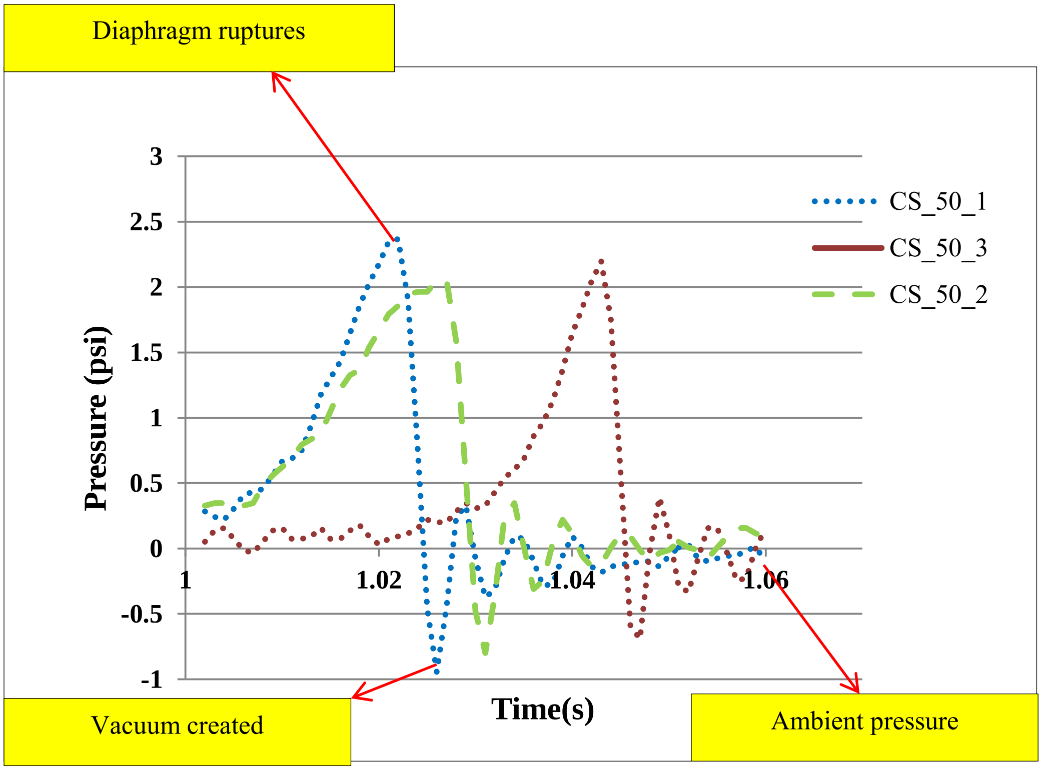

**Figure 4.** The characteristic PvT curves obtained for corn starch at a concentration of 50 g m$^{-3}$ for three replications (Note: CS_50_1 represents the PvT curve obtained for Replication 1 of the corn starch tested at 50 g m$^{-3}$).

Figure 5 shows the schematic diagram of the CAAQES explosible dust testing methodology. The CAAQES chamber was fitted with an Omega DPX-101 pressure sensor connected to a NI-DAQ through a pressure transducer. LabVIEW software was used to record the Pressure vs. Time data. The ignition source was 600 W Eagle glocoil, which can reach a maximum temperature of $360^{o}$C. The temperature of the coil was measured using a temperature gun infrared thermometer. An 8 ½" x 11 ¾" (22 cm by 30 cm) paper diaphragm was used. The diaphragm is engineered by conducting several tests, with different dust samples at various concentrations, such a way that it ruptures if the pressure rise exceeds 2 psi. The dust was dispersed using compressed air through a solenoid valve connected to Dayton timers. A short 1.5 second blast of compressed air at 40 psi was used to disperse the dust in the chamber.

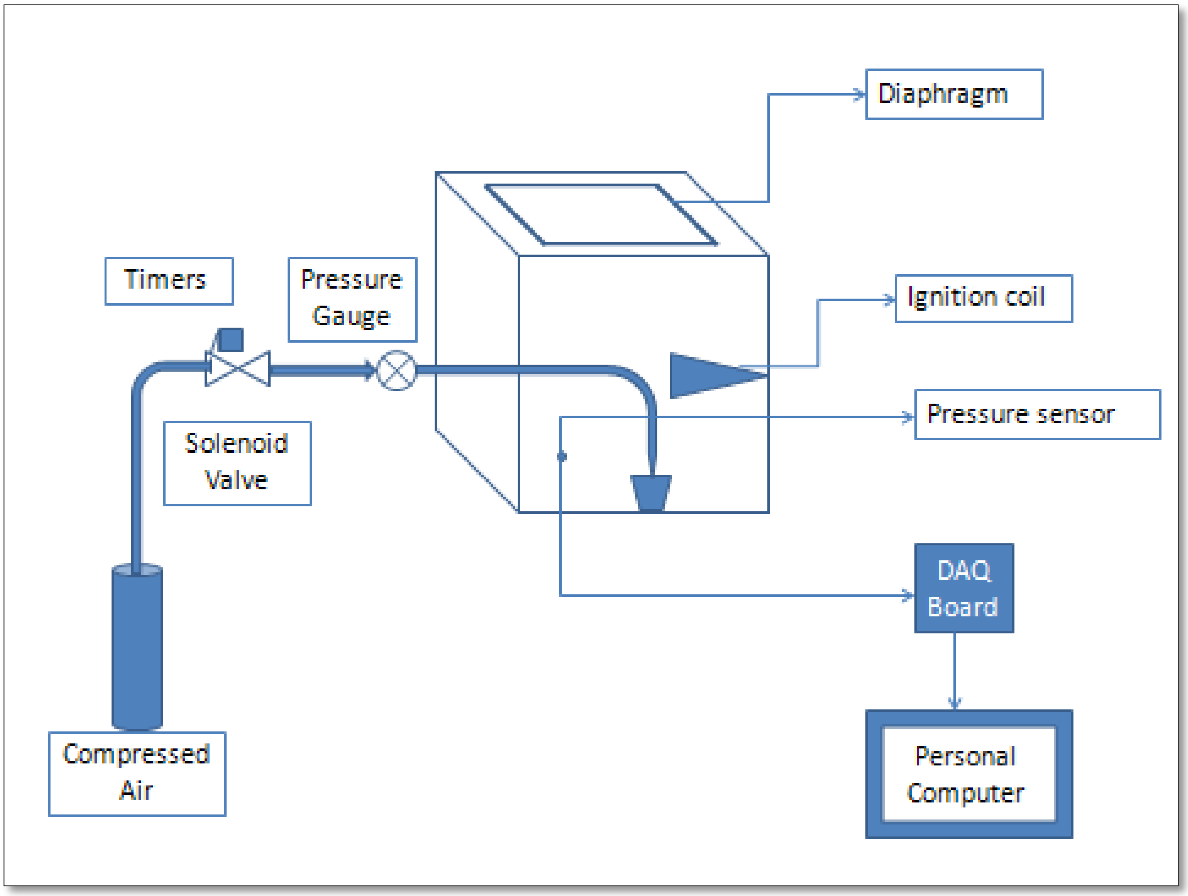

**Figure 5.** Schematic diagram of the CAAQES explosible dust testing method

### Dust cloud volume

The concentration of a test dust in an ASTM chamber was determined by assuming uniform dispersion. The ASTM chamber volume (20-L) was used to define the concentration of a dust. For example, to obtain a concentration of 1000 g $m^{-3}$, we must disperse 20 g of dust into the chamber. Using the CAAQES chamber, it was demonstrated that a deflagration can be achieved without dispersing the dust throughout the chamber. In the CAAQES chamber, only a fraction of the volume of the chamber was used to define the dust concentration. In a grain elevator, the dust concentration in a boot of a leg is not confined by a spherical volume. The same phenomenon was observed in the CAAQES chamber as the dust cloud was not confined by the dimensions of the chamber.

The dust cloud volume in the CAAQES chamber was estimated using corn starch as a standard dust. Corn starch was tested for explosibility using the CAAQES chamber. The mass of corn starch placed in the crucible was reduced step wise until no deflagrations were observed. Each test was replicated for three trials. The lowest mass of corn starch that resulted in one deflagration out of three was the mass of dust that corresponds to the minimum explosible concentration. The lowest mass that resulted in one deflagration out of three for corn starch was 0.43 g. The published MEC of corn starch was 40 g m$^{-3}$ (Palmer, 1973). The volume of the dust cloud occupied by 0.43 g of corn starch to achieve a concentration of 40 g m$^{-3}$ was 10-L (0.01 m$^3$).

Alternatively, a mathematical approach was also used to estimate the volume of the dust cloud using Equation 8:

$$C = \frac{M}{V_A * CA} \tag{8}$$

where,

C = dust concentration, g m$^{-3}$

M= mass of dust dispersed per unit time, g s$^{-1}$

$V_A$= average velocity of particles, m s$^{-1}$

CA= cross-sectional area of dust cloud, $m^2$.

The mass of dust dispersed per unit time (M) was the ratio of the mass of dust in the crucible to the blast time of the compressed air (1.5 s). The cross-sectional area of a dust cloud was determined using $\pi D^2/4$, where D is the diameter of dust cloud. The diameter of the dust cloud was determined by image analysis. Eight agricultural dusts were tested at different concentrations ranging from 25 to 1000 g $m^{-3}$. The diameter of dust clouds ranged from 5 cm to 7 cm. For different cross-sectional area, the dust concentration was determined using Equation 8. The average velocity of particles was determined using test videos. The video frame rate was 30 frames per second. The dust cloud reached the ignition coil in 2 frames. The time taken by the particles to reach the coil was approximated 67 milliseconds. The ignition coil was 6 inches above the crucible. The calculated average velocity using Equation 9 was 2.27 m $s^{-1}$.

$$V_A = \frac{D}{T} \tag{9}$$

where,

$V_A$= Average particle velocity, m $s^{-1}$

D= distance between the crucible and ignition coil, m

T= particles average travel time, s.

The results are shown in Table 4. Figure 6 shows the calculated concentrations for 0.2, 0.4, and 0.6 grams of dust in the CAAQES chamber for different cross-sectional areas of dust cloud. The estimated volume of the dust cloud was 10-L. The dust concentration in the CAAQES chamber was determined using 10-L. For example, to obtain a dust concentration of 50 g m$^{-3}$, we must disperse 0.5 g of dust.

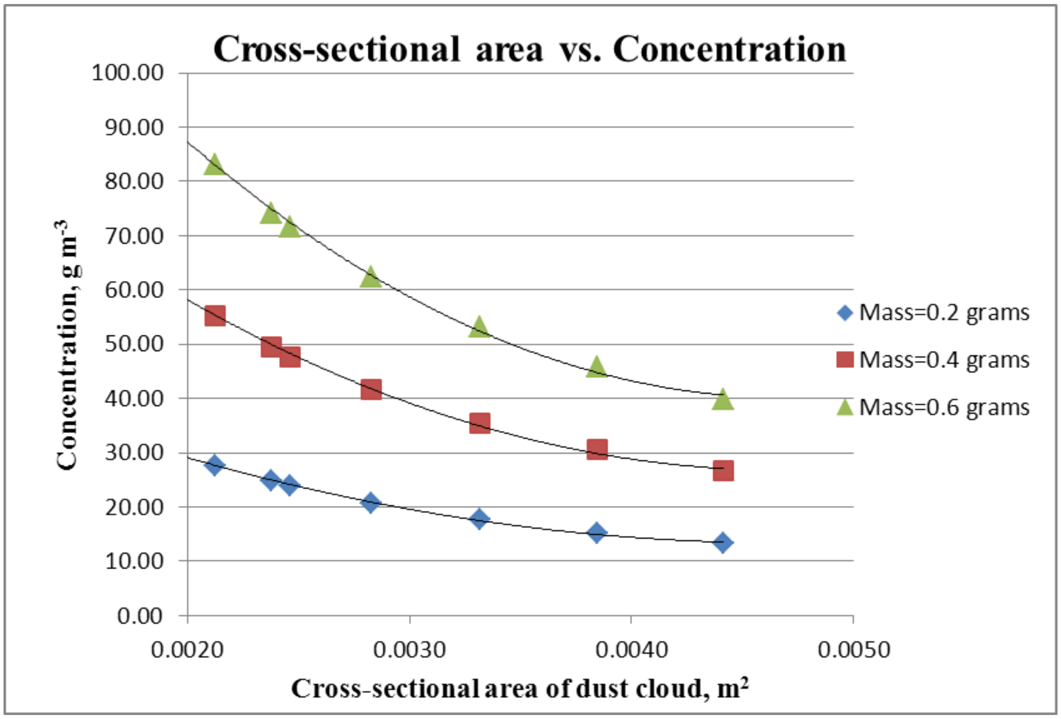

**Figure 6.** Estimated dust concentrations for different cross-sectional area of dust cloud in the CAAQES chamber

**Table 4.** Calculated dust concentration for 0.4 g of dust in the CAAQES chamber

| | | | |
|---|---|---|---|
| Mass | 0.4 | g | |
| Average Particle Velocity | 227 | cm s$^{-1}$ | |
| Blast time | 1.5 | s | |
| **Diameter (cm)** | **Cross-sectional area (cm$^2$)** | **Concentration (g m$^{-3}$)** | **Volume, L** |
| 5 | 19.6 | 60 | 7 |
| 5.2 | 21.2 | 55 | 7 |

**Table 4**. continued.

| **Diameter (cm)** | **Cross-sectional area ($cm^2$)** | **Concentration ($g\ m^{-3}$)** | **Volume, L** |
|---|---|---|---|
| 5.5 | 23.7 | 49 | 8 |
| 5.6 | 24.6 | 48 | 8 |
| 6 | 28.3 | 42 | 10 |
| 6.5 | 33.2 | 35 | 11 |
| 7 | 38.5 | 31 | 12 |
|  | **Average** | **46** | 10 |

## Objective

The objective of this section is to establish the CAAQES explosible dust testing methodology. The specific objectives are as follows:

(a) To determine the MECs of several organic dusts using the CAAQES chamber.

(b) To determine if CGD is explosible.

(c) To demonstrate that a non-spherical chamber can be used to determine MECs and

(d) To compare the MECs determined using the CAAQES chamber with MECs reported by U.S. Bureau of Mines and Palmer (1973).

## CAAQES testing protocol

The protocol for determining the MEC of a dust consists of performing a series of explosion tests for different dust concentrations in the 28.3-L (1 $ft^3$) CAAQES chamber. The CAAQES method was developed based on the explosible dust testing protocols described by Palmer (Palmer, 1973). A series of tests were conducted by reducing the concentration stepwise until no deflagration was observed, testing each concentration for three replications. The lowest concentration at which one deflagration was observed out of three replications was the MEC. The testing procedure consisted of the following steps:

(a) The test dusts were sieved to less than 75 μm as recommended by the ASTM standard.

(b) The sieved dust samples were dried in an oven at 125°C for 30 minutes to reduce the moisture content.

(c) It had been determined by prior testing that only 10-L of the chamber was needed for the CAAQES test protocol.

(d) A precise mass of dust corresponding to the test concentration was placed in the crucible directly below the coil that served as the stationary ignition source.

(e) The coil was set at 360° C prior to dispersing the dust into a dust cloud.

(f) A precise 1.5 second blast of compressed air at 40 psig entrained the dust into a dust cloud.

(g) The dust concentration in the chamber was the ratio of the mass of dust dispersed to a dust cloud volume of 10-L.

(h) An Omega DPX-NPT dynamic pressure sensor was used to measure the pressure rise in the chamber and

(i) The PvT data were recorded utilizing LabVIEW software.

## Design of experiment

The various factors affecting the pressure rise in the CAAQES chamber was studied using Design Expert software. A $2^5$ half-fractional design was chosen for this study. The factors affecting the pressure rise in the chamber and its corresponding levels are shown in Table 5. Corn starch was tested for different factors in the CAAQES chamber.

**Table 5.** The factors affecting the pressure rise and its levels

| **Factors** | **Level A** | **Level B** |
|---|---|---|
| Blast time, s | 1.5 | 3 |
| Heating time of the coil, mins | 2 | 4 |
| Pressure (compressed air), psig | 20 | 40 |
| Dust concentration, g $m^{-3}$ | 40 | 80 |
| Particle size, µm | 75 | 150 |

The data collected and results are shown Appendix D. The response parameter was pressure rise in the CAAQES chamber. The model was significant with a P-value of 0.0011 (P-value < 0.05) at the 95% Confidence Interval. The diagnostic plots were satisfactory. The validity of the model was checked based on the diagnostic plots. The plots are shown in Appendix D. The significant factors are pressure (compressed air), dust concentration, and particle size of the dust. The pressure rise was optimum when the compressed air is at 40 psig at 1.5 seconds blast and ignition time of 2 minutes. Based on this experiment design, the CAAQES chamber was operated with a blast time of 1.5 seconds, compressed air pressure at 40 psig, heating coil time 1.5 minutes since the temperature of the coil reached a steady state after 1.5 minutes, and particle size less than 75 µm.

## Dust characteristics

The ash analysis, moisture content, heating value, particle density, and Particle Size Distribution (PSD) were performed for dust samples. The ash contents and moisture contents of the dust samples were determined by an oven-dry method described in the ASTM standards (ASTM E 1755-08, 2008a; ASTM E 1756-08, 2008b). The PSDs were determined using a Coulter Counter Multisizer (CCM). A bomb calorimeter was used to determine the energy content of dusts. The particle densities of the test dusts were determined using an air pycnometer.

## Results and discussions

The ash contents and moisture contents of the dusts are shown in Table 6. All PSDs are assumed to be lognormal distributions, which are represented by a mass median diameter (MMD) and a geometric standard deviation (GSD). The CCM MMD results were converted from equivalent spherical diameter (ESD) to aerodynamic equivalent diameter (AED) by multiplying the ESD by square root of particle density

(Cooper and Alley, 2002). Table 7 shows the PSDs and particle densities of dusts tested in the CAAQES chamber.

**Table 6.** Ash content and moisture contents of tests dusts (as received)

| Dust Type | Moisture content | Ash content |
|---|---|---|
| | % | % |
| CGD | 1.8 | 87 |
| Corn starch | 7.9 | <1 |
| Wheat flour | 9.5 | <1 |
| Dust XX(a) | 1.6 | 58 |
| Rye flour | 9.4 | <1 |
| Brown rice flour | 10.0 | <1 |
| Sugar | 1.1 | <1 |
| Rice flour | 9.4 | <1 |

(a)Dust XX is an industrial dust coated with a combustible product. The source of this dust cannot be disclosed.

**Table 7.** PSDs of the dusts determined using a Coulter Counter.

| Dust Type | MMD | Particle density | MMD (AED) | GSD |
|---|---|---|---|---|
| | µm | g cm$^{-3}$ | µm | $d_{84.1}/d_{50}$ |
| Brown Rice | 16.9 | 1.5 | 20.6 | 2.1 |

**Table 7**. continued

| Dust Type | MMD | Particle density | MMD (AED) | GSD |
|---|---|---|---|---|
| | μm | g cm$^{-3}$ | μm | $d_{84.1}/d_{50}$ |
| CGD | 15.1 | 3.0 | 26.1 | 2.1 |
| Corn Starch | 17.3 | 1.6 | 21.9 | 1.5 |
| Dust XX | 15.6 | 1.8 | 20.9 | 1.9 |
| Wheat Flour | 21.6 | 1.5 | 26.4 | 1.8 |
| Sugar | 15.4 | 1.6 | 19.5 | 1.3 |
| Rice flour | 15.4 | 1.4 | 18.2 | 1.5 |

The particle density of CGD was almost twice that of all other dusts. Only 13% of the CGD mass was combustible. The 87% mass fraction of non-volatiles likely played a role in rendering CGD non-explosible. It was hypothesized that the inerts in the CGD will prevent the flame from self-propagating through the dust cloud, and we concluded that dust characteristics influence the self-propagation of the flame through the dust cloud. The energy contents of the dusts are shown in Table 8. The energy contents of the all the organic dusts ranged from 15,300 J g$^{-1}$ to 16700 J g$^{-1}$. The energy content of CGD was only 1400 J g$^{-1}$, which is only 10% of all the other organic dusts. The probability of CGD resulting in an explosion with a high inert mass fraction and low energy content is minimal. It was concluded that CGD does not have a MEC was due to its properties. The MECs obtained using the CAAQES chamber is shown in Appendix A.

**Table 8.** The heating values of test dusts determined using a bomb calorimeter.

| Dust type | Energy content, BTU $lb^{-1}$ | Energy content, J $g^{-1}$ |
|---|---|---|
| Corn starch | 6710 | 15,630 |
| Sugar | 6608 | 16,575 |
| Rice flour | 7114 | 15,765 |
| Dust XX | 7142 | 15,395 |
| Rye flour | 7120 | 16,590 |
| Brown rice flour | 7033 | 16,385 |
| Wheat flour | 6766 | 16,640 |
| CGD | 617 | 1,400 |

Figure 7 shows the gin dust tested in the CAAQES chamber at a concentration of 1000 g $m^{-3}$, and Figure 8 shows the characteristic PvT curves of CGD at a concentration of 1000 g $m^{-3}$. The PvT curves indicate that there were no rises in pressure in the chamber. There were no deflagrations observed for any of the concentrations tested for gin dust. It was concluded that CGD did not have an MEC. Hence, it was not an explosible dust.

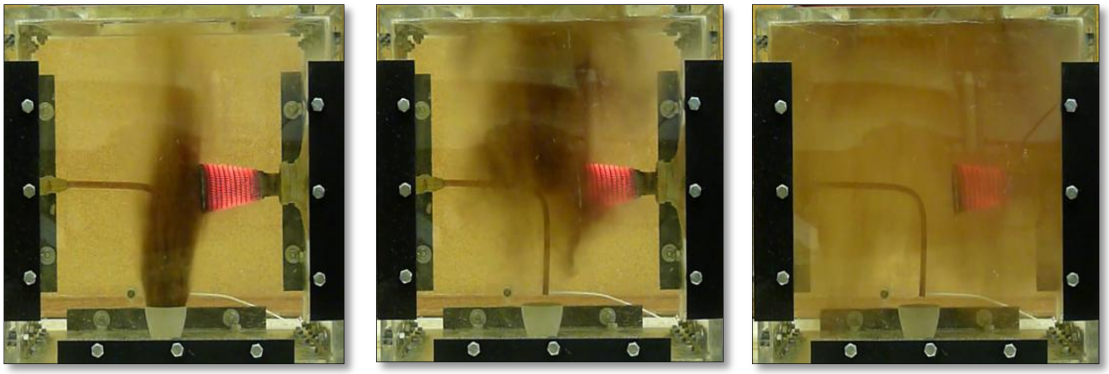

**Figure 7.** Explosibility tests conducted for CGD in the CAAQES chamber. Frame 1 shows the dispersion of gin dust at a concentration of 1000 g $m^{-3}$. Frames 2 and 3 indicate that there were no deflagrations.

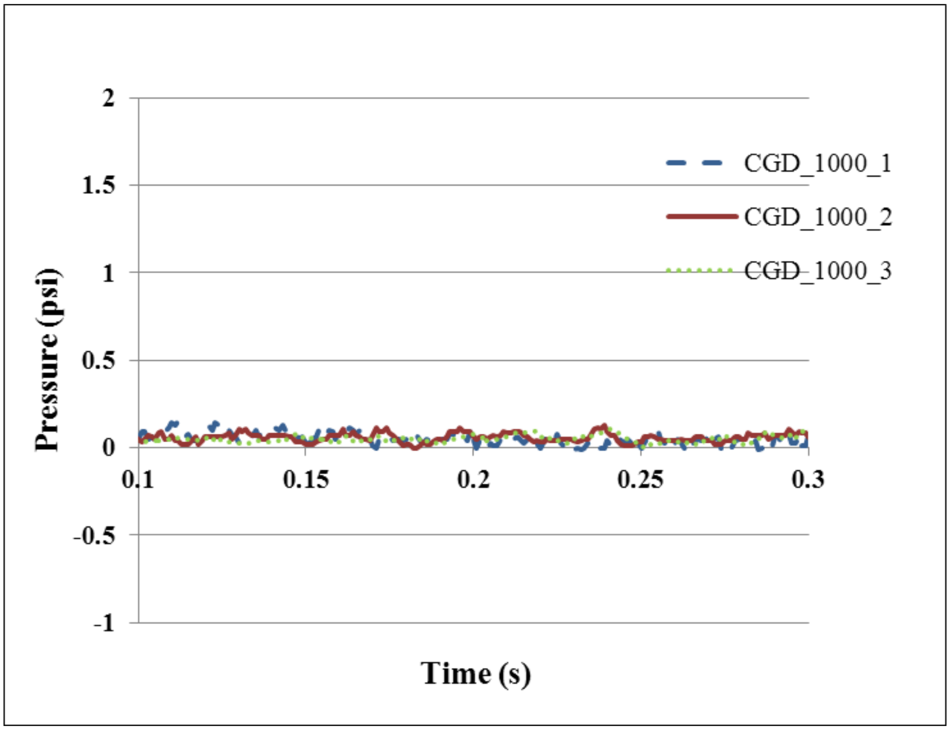

**Figure 8.** The characteristic PvT curves for gin dust at a concentration of 1000 g $m^{-3}$. No deflagrations were observed for the three replications. The flat lines indicate that there is no rise in pressure in the chamber during a test.

Figure 9 shows the deflagration occurred in the CAAQES chamber for the Dust XX at a concentration of 57 g $m^{-3}$. Figure 10 shows the characteristic pressure vs. time curve for Dust XX at a concentration of 57 g $m^{-3}$. Deflagrations were observed for replication (Rep) 2 and 3.

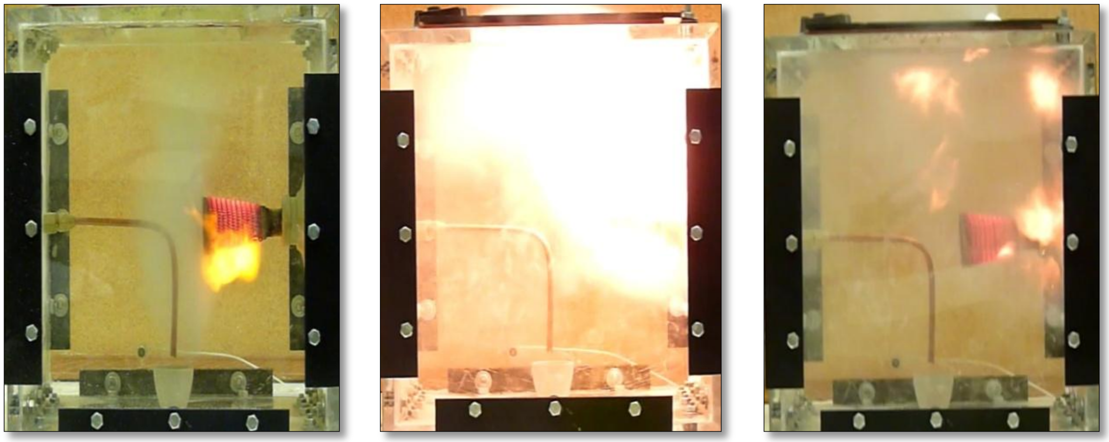

**Figure 9.** A dust explosion fueled by Dust XX at a concentration of 57 g $m^{-3}$.Frame 1 shows the dispersed dust cloud is ignited by the heating coil. Frame 2 shows the self-propagating flame rupturing the diaphragm. Frame 3 shows the flame leaving the chamber.

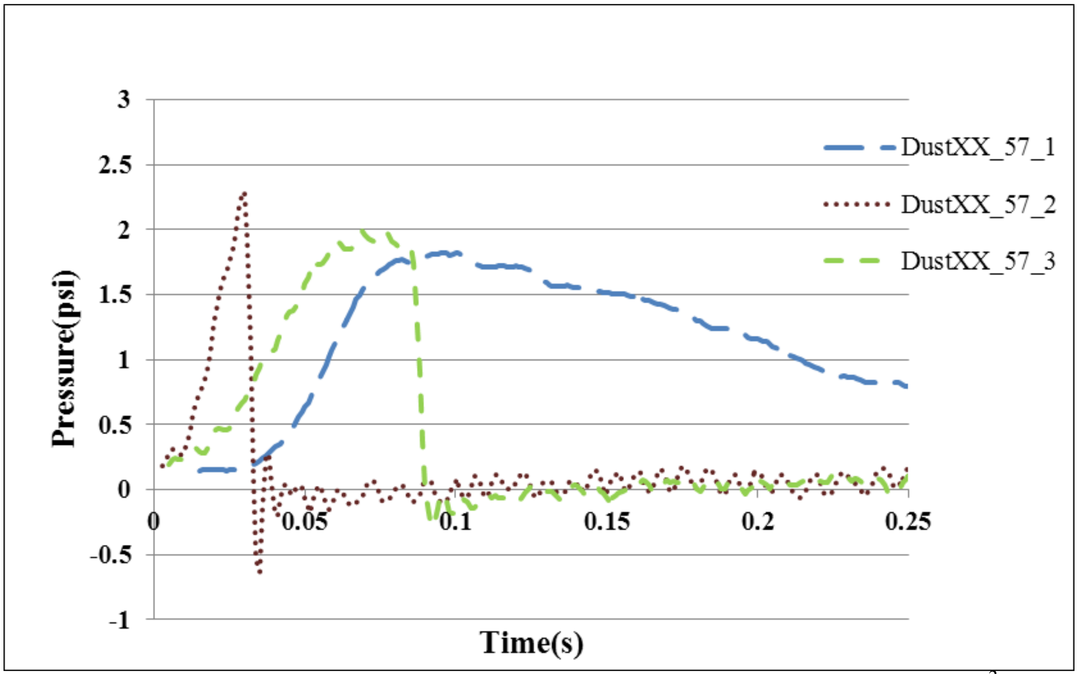

**Figure 10.** Characteristic PvT curves for Dust XX at a concentration of 57 g $m^{-3}$. Deflagrations were observed for Rep 2 and 3.

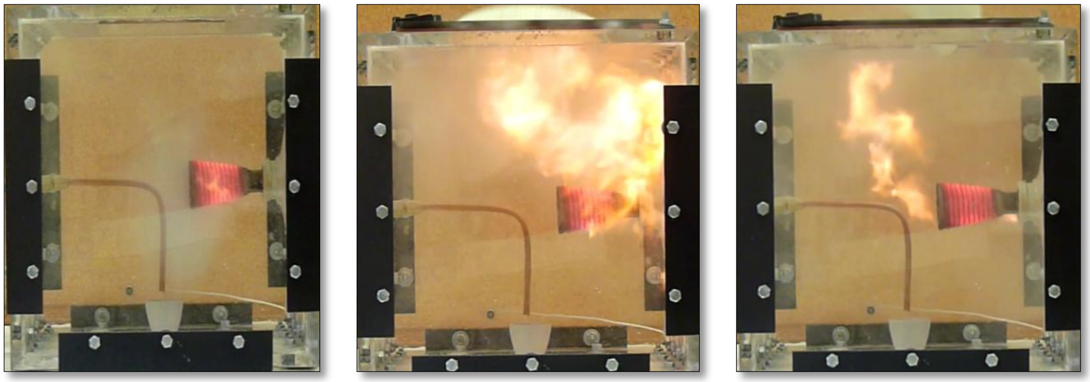

**Figure 11.** A deflagration observed in the CAAQES chamber for wheat flour at a concentration of 90 g $m^{-3}$

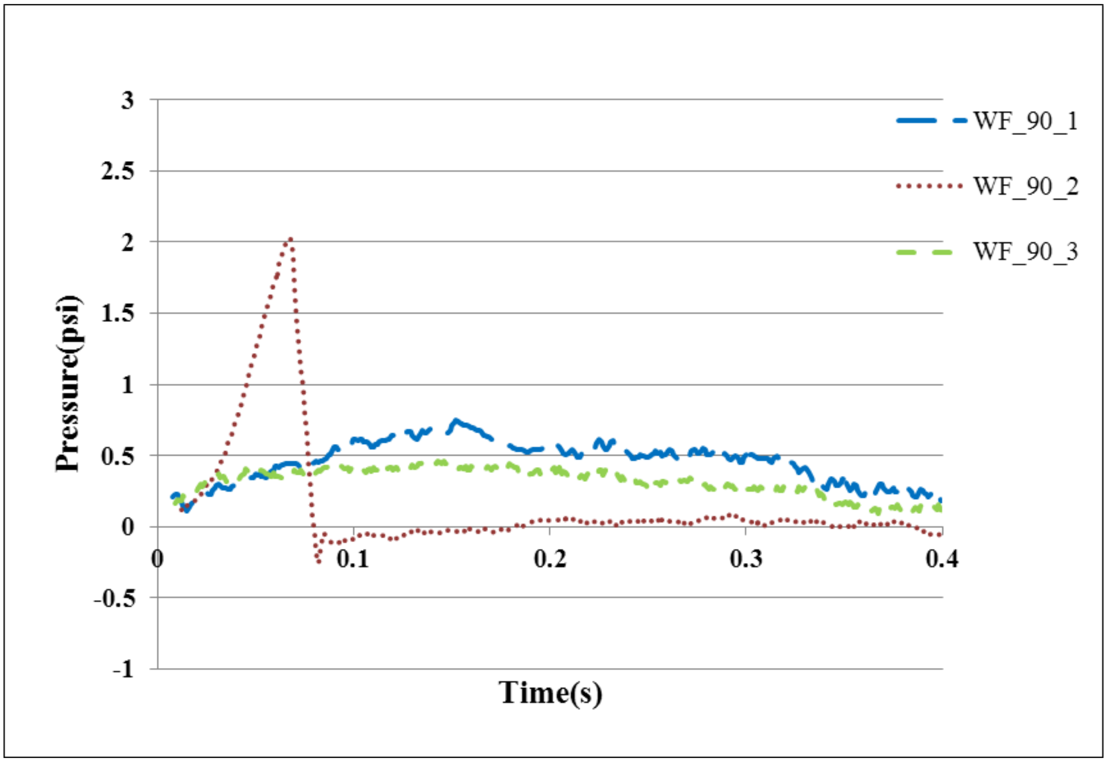

**Figure 12.** Characteristic PvT curves obtained for wheat flour at a concentration of 90 g $m^{-3}$

Figure 11 and Figure 12 shows the dust explosion fueled by wheat flour, and the characteristic PvT curves at a concentration of 90 g $m^{-3}$, respectively. Figure 13 and Figure 14 shows the deflagration and characteristic PvT curves for rye flour at a concentration of 81 g $m^{-3}$.

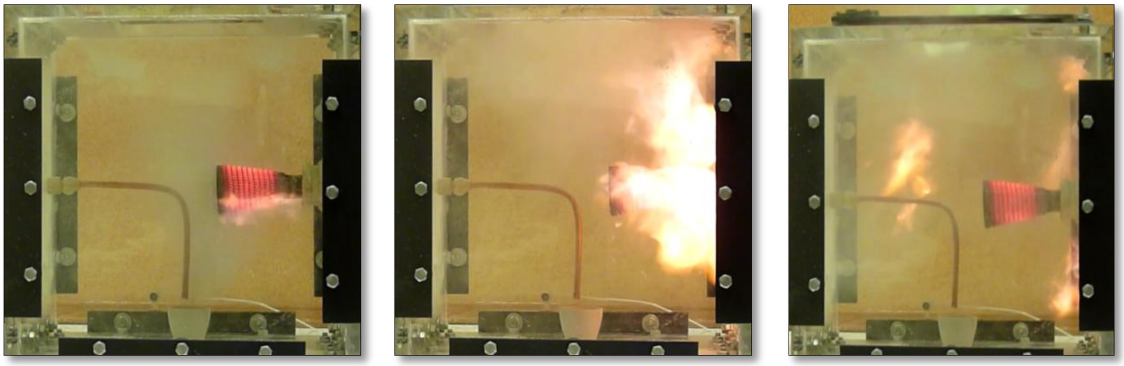

**Figure 13.** A deflagration observed in the CAAQES chamber for rye flour at 81 g $m^{-3}$

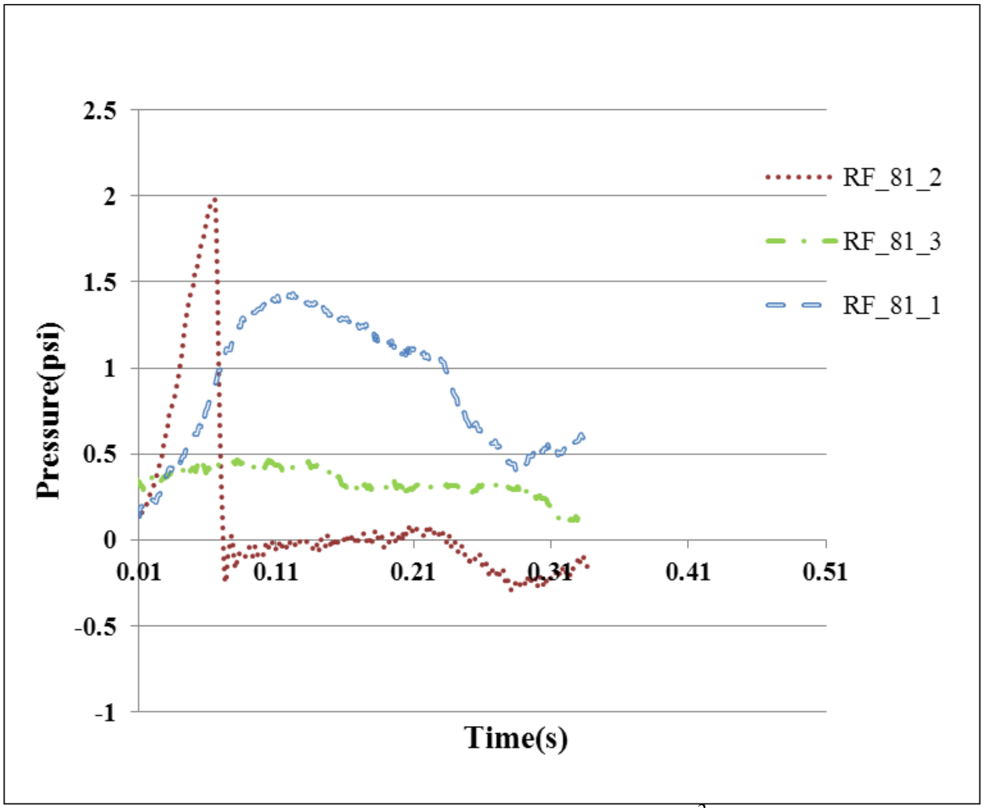

**Figure 14.** Characteristic PvT curves for rye flour at 81 g $m^{-3}$. No deflagrations were observed for Rep 3 and 2.

Figure 15 and Figure 16 shows the deflagration and characteristic PvT curves of brown rice flour at a concentration of 72 g m$^{-3}$. Figure 17 and Figure 18 shows the deflagration, and characteristic PvT curves for sugar at a concentration of 60 g m$^{-3}$.

**Figure 15.** A deflagration observed in the CAAQES chamber for brown rice flour at a concentration of 72 g m$^{-3}$

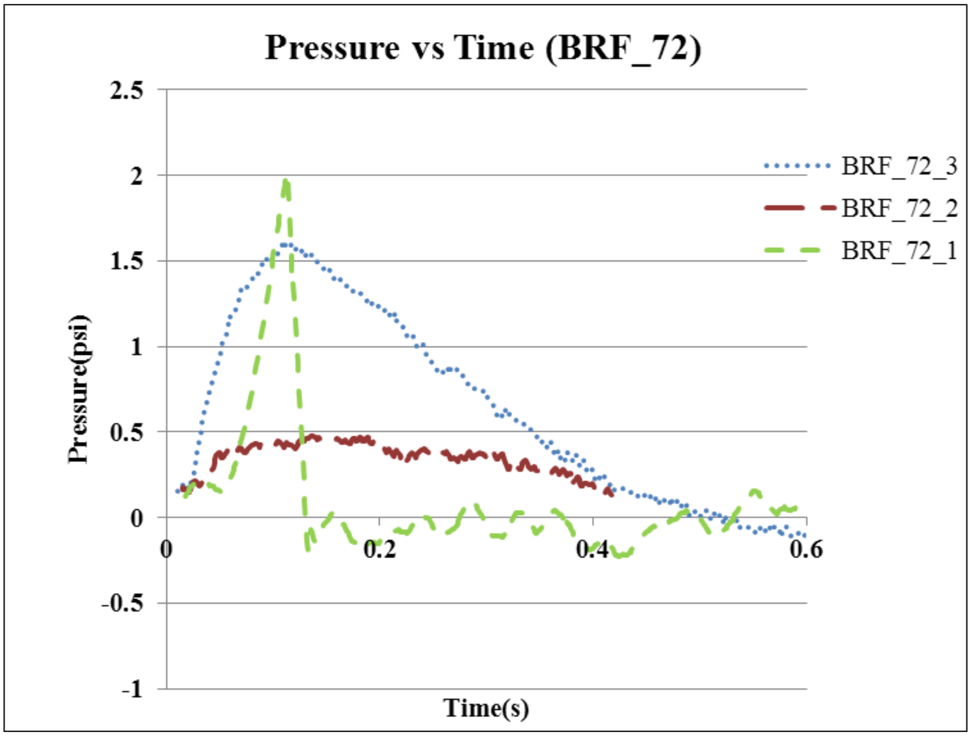

**Figure 16.** Characteristic PvT curves for brown rice flour at a concentration of 72 g $m^{-3}$. No deflagrations were observed for Rep 2 and 3.

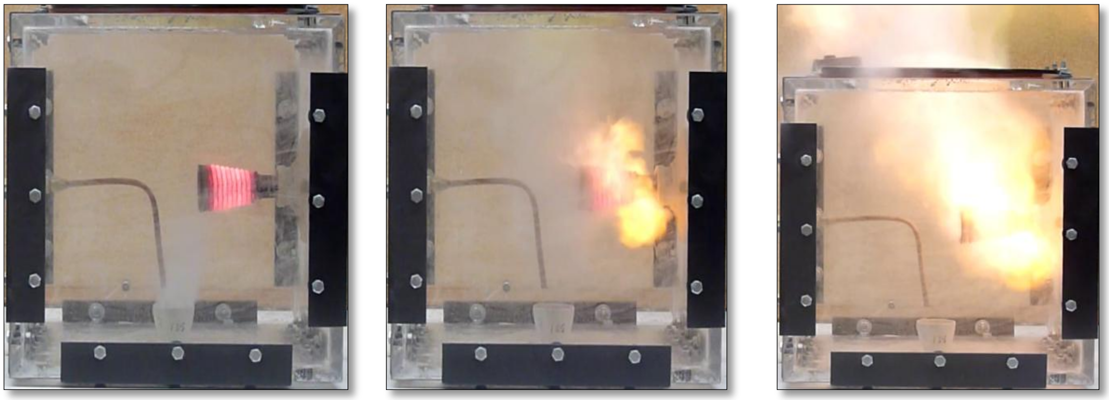

**Figure 17.** A deflagration observed in the CAAQES chamber for sugar at 60 g $m^{-3}$

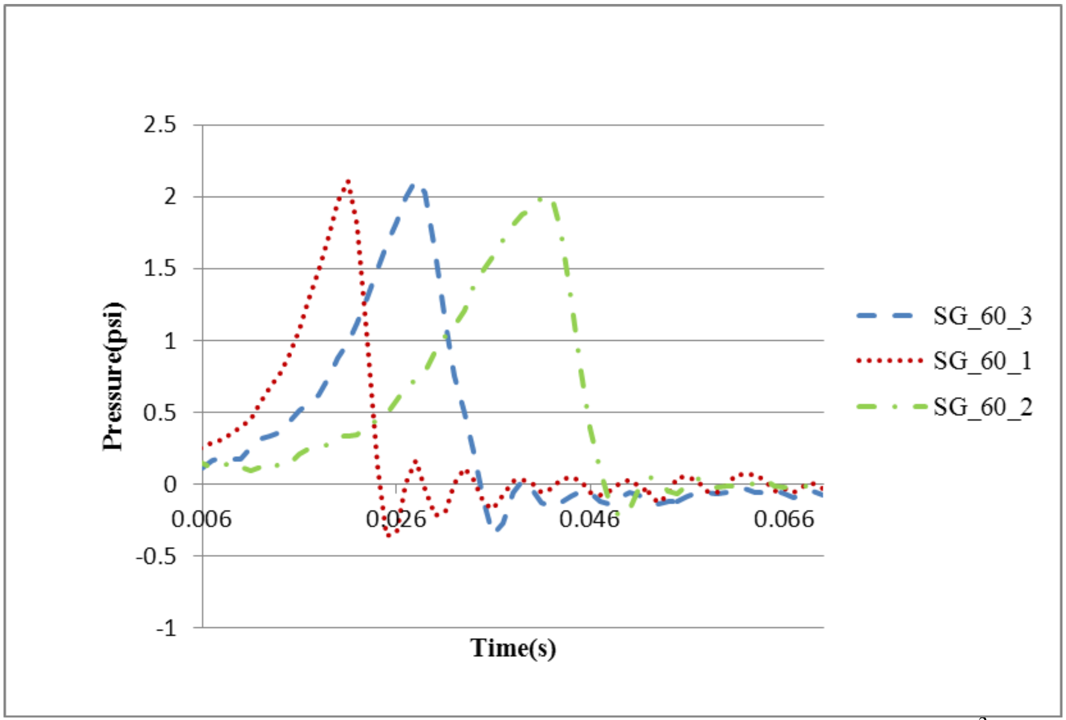

**Figure 18.** Characteristic PvT curves for sugar at a concentration of 60 g m$^{-3}$. Deflagrations were observed for all the Reps.

Figure 19 shows the self-propagating flame due to ignition of dust cloud at a concentration of 40 g m$^{-3}$ (rice flour) and there was no sufficient pressure rise to rupture the diaphragm. Figure 20 shows the characteristic PvT curves for rice flour at a concentration of 40 g m$^{-3}$. A deflagration was observed for Rep 2.

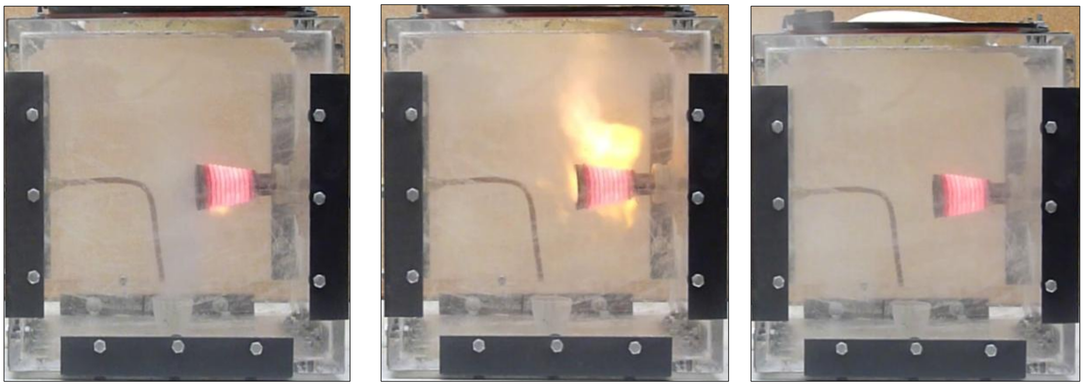

**Figure 19.** An explosion test of rice flour at a concentration of 40 g m$^{-3}$

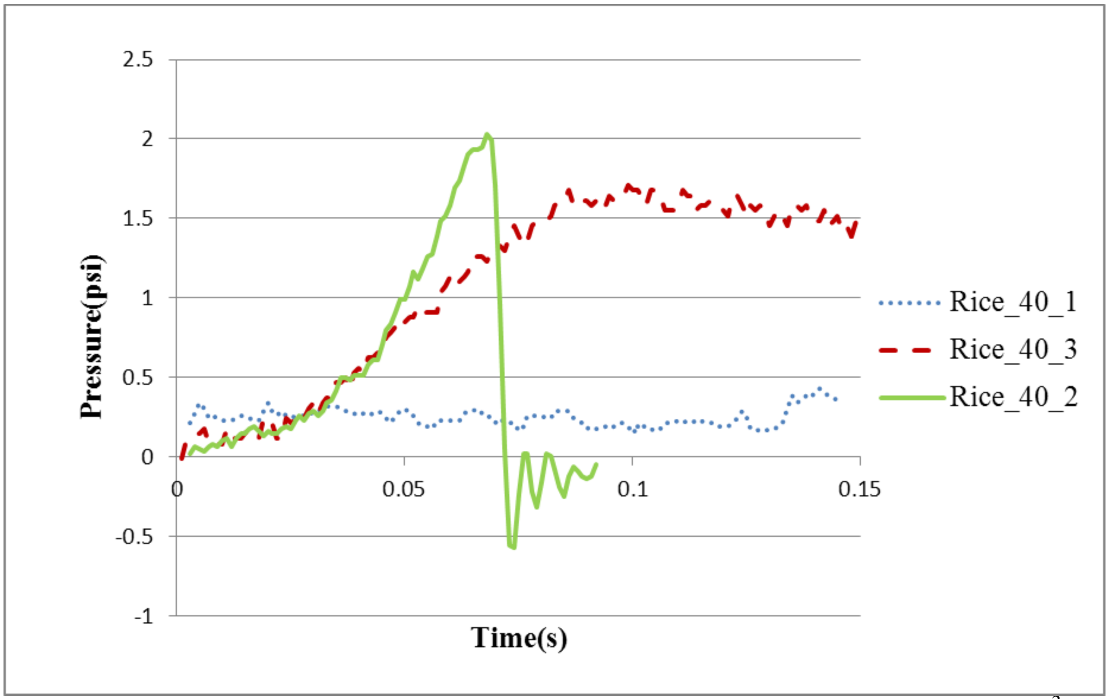

**Figure 20.** The Characteristic PvT curve for rice flour at a concentration of 40 g m$^{-3}$

The MECs obtained using the CAAQES chamber was compared with the MECs published by U.S. Bureau of Mines and Palmer (1973), and are shown in Table 9.

**Table 9.** Comparison of MEC determined using the CAAQES chamber and 1.2-L Hartmann tube.

| Dust type | 1.2-L Hartmann Tube | CAAQES chamber |
|---|---|---|
| Brown Rice | 85(a) | 72 |
| Corn Starch | 40(a) | 25 |
| Dust XX | NA(b) | 54 |
| Wheat Flour | 65(a) | 85 |
| Rice flour | 50(c) | 28 |
| Sugar | 35(c) | 30 |
| Rye flour | NA(b) | 81 |

(a)Fire Protection Handbook, 13th Edition, 1969
(b)Not available
(c)Dust Explosions and Fires, Palmer, 1973

## Summary

The MECs of several organic dusts were determined using the CAAQES methodology. Dust explosions can be prevented by reducing the MECs locations by dust suppression using mineral oil or water, and installing pneumatic dust control systems that can capture the dust entraining in air at the grain transfer points. The CAAQES protocol determines if a dust is explosible based upon the existence of a MEC. The CAAQES testing methodology yields reliable and accurate results compared to the ASTM method for the following reasons:

1. The CAAQES testing protocol ensures the flame self-propagates through the dust cloud, if the dust concentration is at or above the MEC by using a stationary source and a diaphragm.
2. The CAAQES chamber prevents the tests from being oxygen-limited, while the ASTM chamber contains sufficient oxygen to combust only 2 g of dust.
3. The ASTM method uses only one indicator to identify a deflagration in the chamber. The CAAQES method uses three indicators to identify a deflagration:
    a. The diaphragm must rupture while the pressure rises due to a self-propagating flame.
    b. The self-propagating flame must leave the chamber and
    c. A characteristic Pressure vs. Time curve is obtained
4. The MECs obtained using the CAAQES chamber were similar to the MECs published by Palmer and U.S. Bureau of Mines.
5. The CGD does not have a MEC. Hence, it is non-explosible.
6. The high inert mass fraction with a low energy content of CGD rendered it non-explosible.

# CHAPTER IV

# IMPACT OF INERT MASS FRACTION ON EXPLOSIBLE DUSTS[*]

## Introduction

Further studies were carried out to determine why cotton gin dust (CGD) was not explosible. The CGD does not have a minimum explosible concentration (MEC) due to its characteristics. It consisted of only 13% volatiles with a heating value of 1400 J $g^{-1}$. Several factors, such as the formation of dust cloud, ignition energy, Particle Size Distribution (PSD), dust concentration, turbulence, presence of inert dust, and moisture content, influence the propagation of a flame in a deflagration (Palmer, 1973 & Bartknecht, 1989). The dusts characteristics, such as inert mass fraction, energy content, Particle Size Distribution (PSD), and particle density were considered for this research to study the properties affecting the explosibility of a dust. Explosibility tests were conducted to determine the percentage of inerts required to prevent the flame propagation using the CAAQES chamber. Additionally, a theoretical approach was developed to determine the percentage of inerts required to suppress the explosibility of dusts based on the combustible particle distance, assuming uniform dispersion. The hypothesis is that, at a specific concentration, the combustible particles must be at a certain distance for a flame to propagate from one burning particle to another. The particle distance was determined using particle density, ash content, and assuming all the

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[*] Part of this chapter is submitted for publication "Impact of inert mass fraction on explosible dusts" Ganesan. B, C.B. Parnell Jr., R.O. McGee. 2013. *Transactions of ASABE (in peer review)*

particles in a dust cloud are same size with a uniform dispersion. To study the impact of inert mass fraction, Fullers earth, an inert dust, was admixed with the organic dusts. The effect of inert mass fraction on MECs was also studied using corn starch (CS) and sugar (SG). A thorough study was conducted to demonstrate the impact of inert mass fraction, energy content, and combustible particle distance on the flame propagation in the CAAQES chamber.

## Objective

The objective is to determine if dust characteristics affects the explosibility of a dust. The specific objectives are as follows:

(a) To demonstrate that the inert mass fraction affects the MECs of dusts.

(b) To determine if characteristics of CGD rendered it non-explosible.

(c) To calculate the distance between the combustible particles at a specific concentration and show that the particles must be at a certain distance to enable the flame propagation and

(d) To develop a theoretical approach to determine the percentage of inerts required to prevent the flame propagation for organic dusts based upon the combustible particle distance.

## Methodology

### *Prevention of flame propagation using fuller's earth*

The inert dust, Fuller"s earth was mixed with the organic dusts at different proportions and tested in the CAAQES chamber. The proportion of inert dust was increased, and the admixed dusts were tested until no deflagrations were observed. Each admixed dust concentration was tested for three replications, and the percentage of inerts required to prevent the flame propagation was determined. The testing procedure consisted of the following steps:

(a) The test dusts and inert dust (Fuller"s earth) were sieved to less than 75 μm.

(b) The test dust and Fuller"s earth were mixed in a crucible and placed directly below the heating coil.

(c) A precise 1.5 second compressed air blast at 40 psig was directed into the crucible that entrains the dust mixture into a dust cloud.

(d) The heating coil was set at a temperature of 360$^{o}$C before dispersing the dust.

(e) The admixed dust concentration was determined by using only a fraction of the volume of the chamber. The estimated dust cloud volume in the CAAQES chamber was 10-L.

(f) A pressure sensor was used to measure the rise in pressure in the chamber.

(g) The PvT data were recorded using LabVIEW.

(h) The inert mass fraction was increased incrementally and tests were conducted until no deflagrations were observed.

Figure 21 shows a deflagration of corn starch with Fuller‟s earth at a concentration of 170 g m$^{-3}$. Frame 1 shows the dispersion of admixed dust. Frame 2 shows the dust cloud ignited by the stationary source resulting in a self-propagating flame. Frame 3 shows the rupturing of the diaphragm and the flame leaving the chamber. Figure 22 shows the characteristic Pressure vs. Time curves for corn starch and Fuller‟s earth mixture at a concentration of 170 g m$^{-3}$ (100 g m$^{-3}$ of corn starch and 70 g m$^{-3}$ of Fuller‟s earth). A deflagration was observed for Replication (Rep) 3, and no deflagrations were observed for reps 1 & 2.

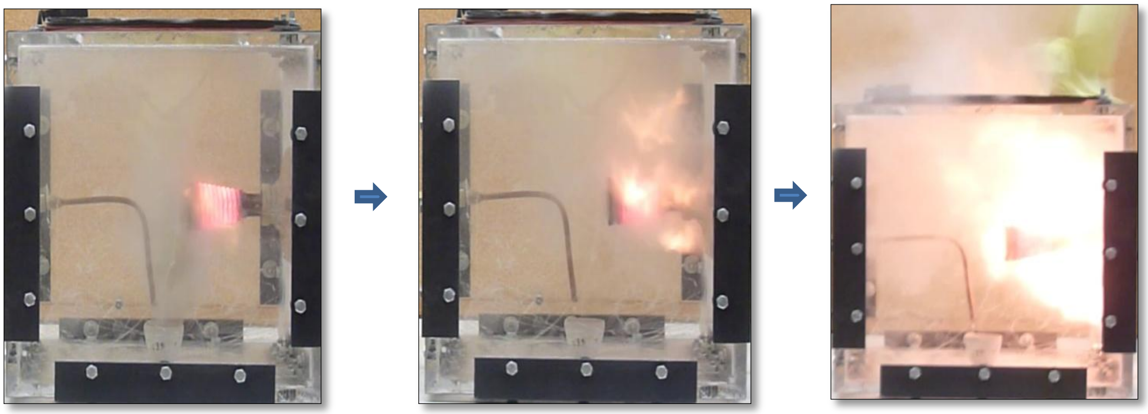

**Figure 21.** A deflagration of corn starch and Fuller‟s earth dust mixture at 170 g m$^{-3}$

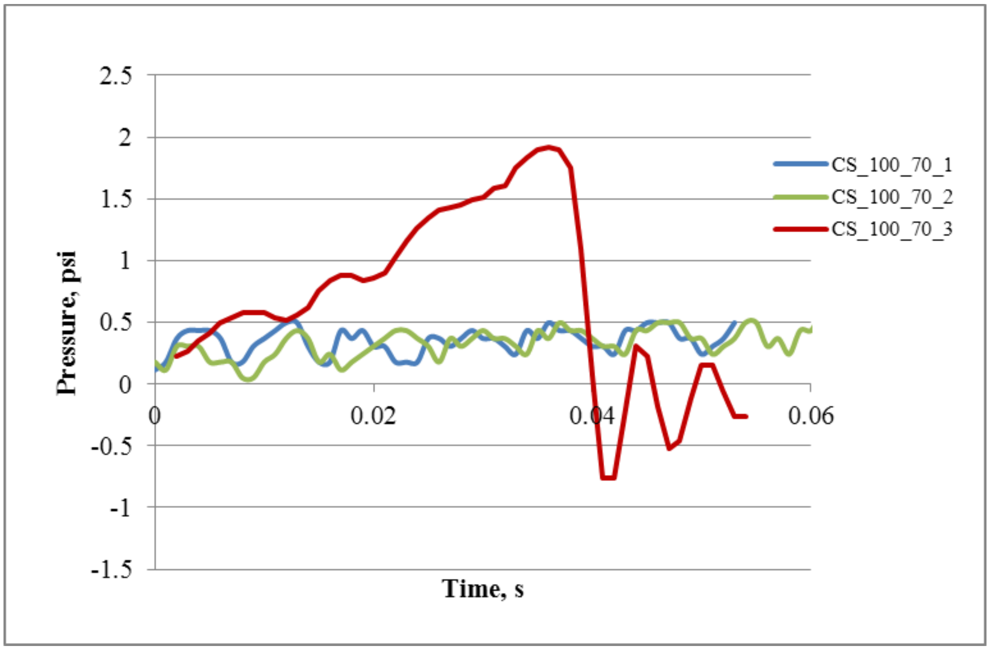

**Figure 22.** The characteristic PvT curves for corn starch and Fuller"s earth mixture at 170 g m$^{-3}$

### *Effect of inert mass fraction on MECs*

The correlation between the inert mass fraction and MECs was determined by conducting explosibility tests by mixing organic dusts with Fuller"s earth. The inert mass fraction of corn starch and sugar was increased incrementally by adding Fuller"s earth. The inert mass fraction was increased from 5% to 40%. The MECs of admixed dusts with different proportions of inert dust were determined using the CAAQES chamber. Figure 23 shows the test results obtained using the CAAQES chamber for sugar and corn starch.

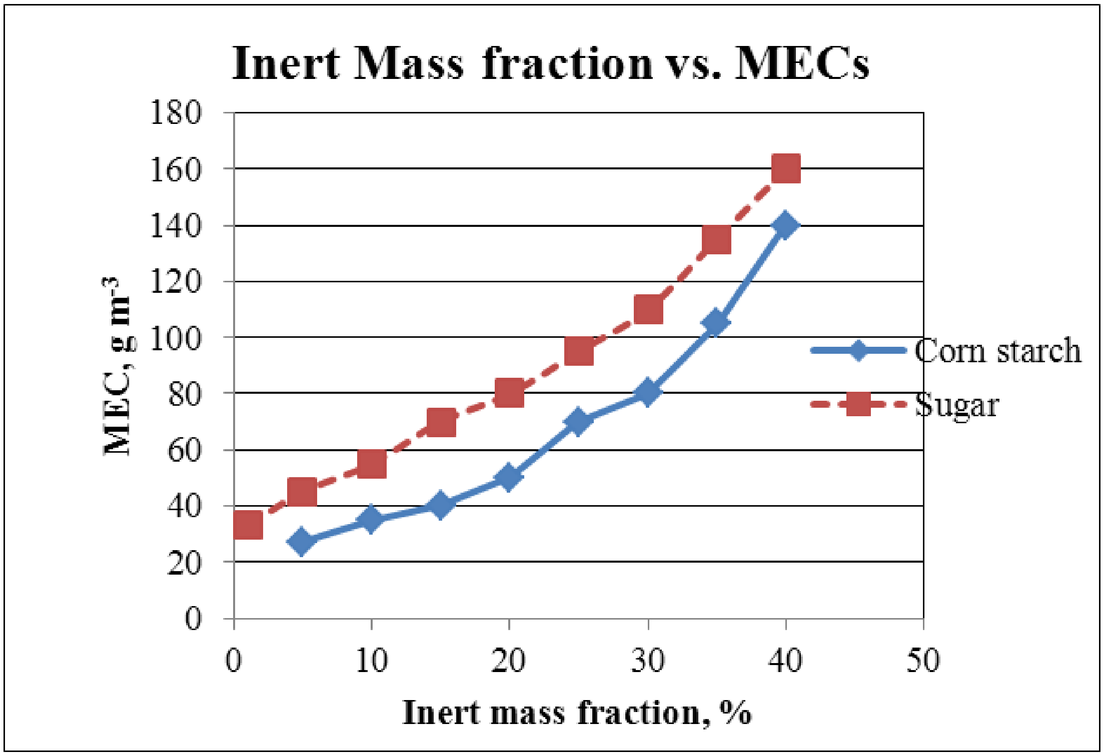

**Figure 23.** MECs for dust mixture (Explosible + Inerts) determined using the CAAQES chamber

***Analytical procedure: particle distance and inert percentage***

At a specific concentration, the average distance between the combustible particles in the CAAQES chamber was calculated. It was assumed that the dust dispersion was uniform and the particles were the same size. The mass median diameter (MMD) was taken as the particle diameter. The average particle distance was calculated using MMD, particle density, and percentage volatiles. A theoretical approach was developed using the particle distance and inert mass fraction to determine the inert percentage required to prevent a deflagration. The steps involved in calculating the average particle distance were as follows:

(a) Each particle was assumed to be surrounded by an imaginary sphere of diameter, $d_s$.

(b) The MMD was taken as the diameter of each particle, $d_p$.

(c) The volume of a particle ($V_p$) was calculated using the following equation

$$V_p = \frac{\pi d_p^3}{6} \tag{10}$$

(d) The particle density was determined using an air pycnometer, $P_{d.}$

(e) The mass of each particle was the product of particle density ($P_d$) and volume of a particle ($V_p$).

(f) The number of particles was the ratio of total mass of dust to mass of each particle, N

(g) The average distance between the particles was determined by

$$d_s = \left(\frac{0.01*6}{N*\pi}\right)^{1/3} \tag{11}$$

where 0.01 = volume of the dust cloud in the CAAQES chamber (10-L).

Figure 24 shows the theoretical average distance between the combustible particles for different concentrations of various agricultural dusts. From the Figure 24, the distance between the particles for sugar at MEC (30 g $m^{-3}$) is 450 μm. If the distance between the particles is greater than 450 μm, there will be a reaction in the chamber (deflagration). The inert mass fraction required to prevent the flame propagation was determined theoretically. It was hypothesized that the increase in inert mass fraction increases the distance between the combustibles and incapacitates the flame propagation.

The volatile percentage of the admixed dusts was reduced due to the addition of Fuller"s earth, thus increasing the average volatile particle distance. The inert mass fraction was increased until the average combustible particle distance was greater than average combustible particle distance at MEC. The inert mass fraction for which the average particle distance exceeds the MEC-average particle distance was the theoretical inert percentage required to prevent the flame propagation. The results are shown in Table 13.

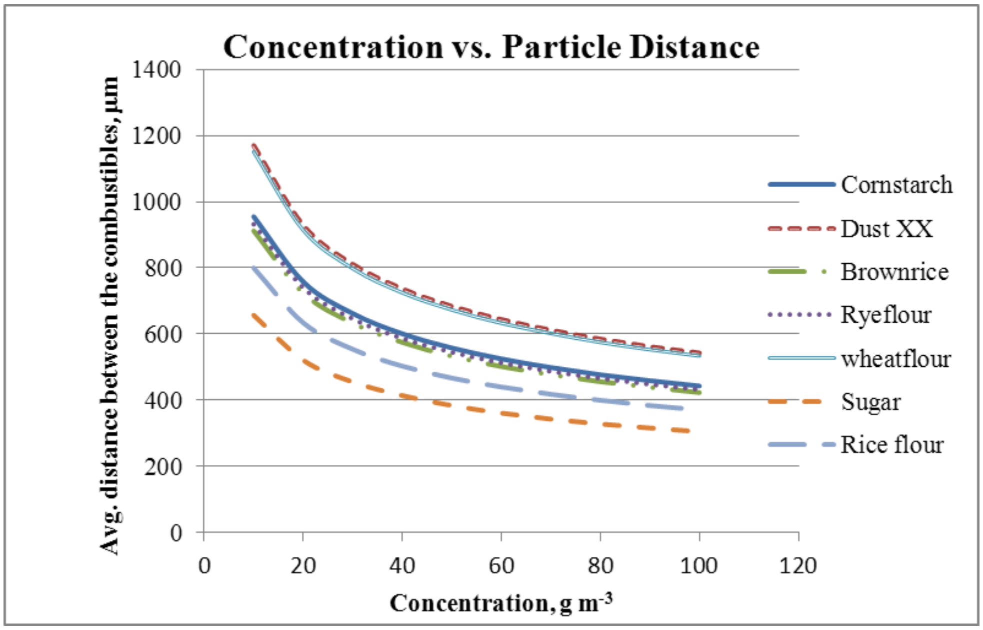

**Figure 24.** The average particle distance between the volatiles for organic dusts at different concentrations

## Results and discussions

The organic dusts tested in the CAAQES chamber with Fuller‟s earth were corn starch, rice flour, sugar, wheat flour, brownrice flour, Dust XX, and rye flour and the results are shown in Table 10. Approximately 50% of inert (Fuller‟s earth) suppressed the explosibility of the dusts (Ganesan et al., 2013). Palmer (1973) reported that the minimum proportion of inert dust required to prevent flame propagation was 60-65%. The energy contents of the test dusts were determined using a bomb calorimeter. The energy content of CGD was only 10% of energy content of other dusts. It was observed that energy content of a dust should be above 7000 J $g^{-1}$ to facilitate a deflagration, as 50% of inerts prevented the deflagration for all dusts.

**Table 10.** The percentage of inerts required to prevent the flame propagation in the CAAQES chamber

| Dust type | Dust Concentration ($g\ m^{-3}$) | Inert Concentration ($g\ m^{-3}$) | Mixture concentration ($g\ m^{-3}$) | Inert Percentage % | No. of Deflagration observed (Out of 3 replications |
|---|---|---|---|---|---|
| Corn starch | 100 | 70 | 170 | 42 | 1 |
| Corn starch | 100 | 85 | 185 | 46 | 1 |
| **Corn starch** | **100** | **89** | **189** | **48** | **0** |
| Rice flour | 100 | 80 | 180 | 45 | 1 |
| **Rice flour** | **100** | **100** | **200** | **50** | **0** |

**Table 10**. continued

| Dust type | Dust Concentration (g m$^{-3}$) | Inert Concentration (g m$^{-3}$) | Mixture concentration (g m$^{-3}$) | Inert Percentage % | No. of Deflagration observed (Out of 3 replications |
|---|---|---|---|---|---|
| Sugar | 70 | 30 | 100 | 30 | 3 |
| Sugar | 55 | 45 | 100 | 45 | 1 |
| **Sugar** | **53** | **47** | **100** | **47** | **0** |
| Dust XX | 100 | 80 | 180 | 45 | 1 |
| **Dust XX** | **100** | **95** | **195** | **48** | **0** |
| **Rye flour** | **100** | **98** | **198** | **49** | **0** |
| **Brownrice** | **100** | **90** | **190** | **47** | **0** |
| **Wheat flour** | **120** | **80** | **200** | **40** | **0** |

**Table 11.** Theoretical and actual mass inert fraction required to prevent a deflagration for dusts tested in the CAAQES chamber

| Dust Type | MEC, g m$^{-3}$ | Avg. distance between particles, µm | Energy content, J g$^{-1}$ | Theoretical Inert mass fraction,% | Actual Inert mass fraction, % |
|---|---|---|---|---|---|
| Corn starch | 25 | 700 | 15,630 | 49 | 48 |
| Sugar | 30 | 455 | 16,575 | 64 | 47 |
| Rice flour | 28 | 567 | 15,765 | 59 | 50 |
| Dust XX | 52 | 675 | 15,395 | 49 | 47 |

**Table 11**. continued

| Dust Type | MEC, g $m^{-3}$ | Avg. distance between particles, µm | Energy content, J $g^{-1}$ | Theoretical Inert mass fraction,% | Actual Inert mass fraction, % |
|---|---|---|---|---|---|
| Rye flour | 81 | 464 | 16,590 | 43 | 49 |
| Brown rice | 72 | 472 | 16,385 | 40 | 47 |
| Wheat flour | 85 | 564 | 16,640 | 23 | 40 |
| CGD | No MEC | NA | 1,400 | NA | NA |

Table 11 shows the particle distance at MECs of different dusts with corresponding ash content and energy content. A deflagration was prevented for all the organic dust by increasing the mass fraction of Fuller"s earth up to 50%. The inert percentage of CGD was 87% with a heating content of 1400 J $g^{-1}$. The energy content of CGD was only 10% of energy contents of other dusts. It was concluded that the characteristics of CGD rendered it non-explosible. The high mass fraction of inerts inhibits the flame propagation rendering a dust non-explosible. The correlation between the theoretical and actual inert mass fraction required to prevent the flame propagation was significant with a P-value of 0.047 at the 95% confidence interval. Figure 25 shows the actual and theoretical inert mass fraction required to suppress the explosibility of dusts. It was also observed that the combustible particles should be 450 to 700 mm to facilitate the flame propagation in the CAAQES chamber. The distance between the particles for CGD was not in this range for any of the concentrations.

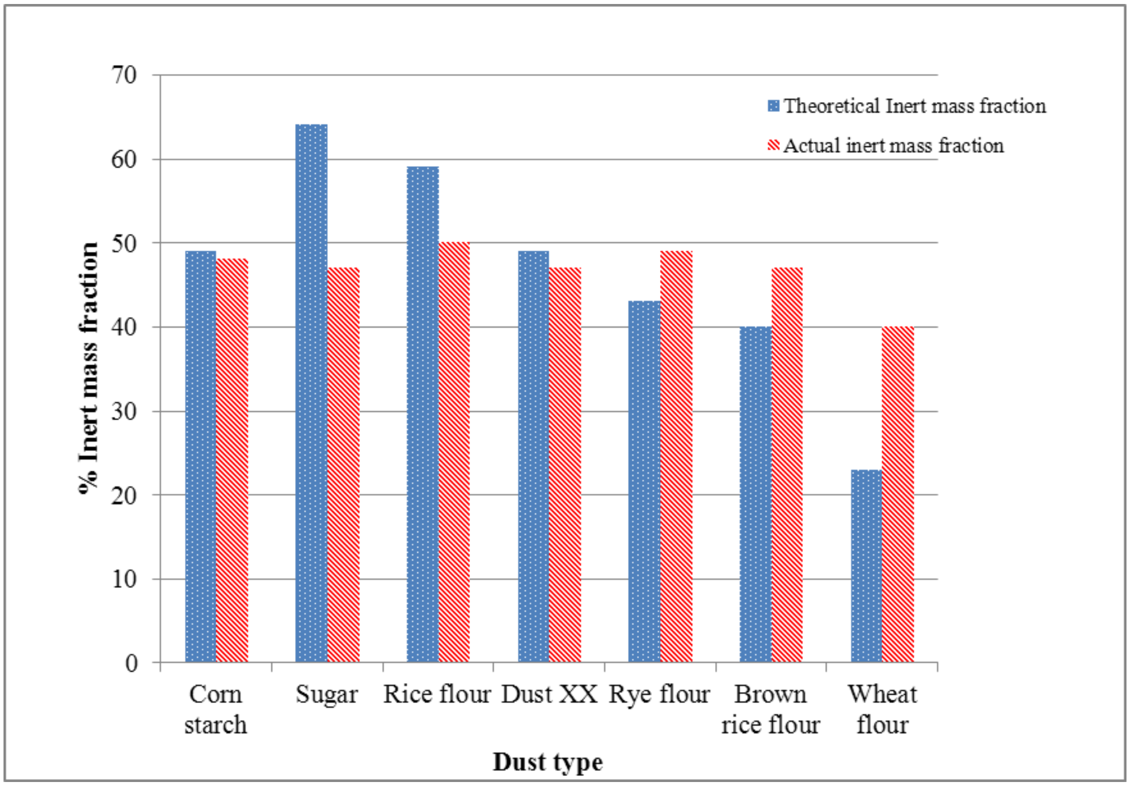

**Figure 25.** Theoretical and actual inert mass fraction required to prevent the flame propagation

## Summary

A dust must be classified as explosible based upon the existence of a MEC. The current ASTM testing protocol does not use MEC as a criterion to classify a dust. CGD consisting of 87% inerts with a low energy content of 1400 J $g^{-1}$ will not result in a deflagration. Using pressure rise as the only indicator to determine a deflagration in the ASTM chamber resulted in classifying CGD as Class „A" explosible dust, contrary to the CAAQES results. A dust must be classified based on a testing system designed by

CAAQES personnel or similar protocols used by Palmer and U.S. Bureau of Mines as the current ASTM standard explosible testing standard yields inaccurate results.

*A pre-test analysis must be conducted before testing a dust for explosibility*. The pre-tests must include ash analysis, PSD, particle density and Heating value. The test results from this study shows that the dust characteristics influence the MEC of a dust. The significant findings are as follows:

(a) The inert mass fraction, energy content, volatile particle distance at a specific concentration affects the flame propagation.

(b) The high inert mass fraction of 87% with a very low heating value (1400 J $g^{-1}$) rendered CGD non-explosible. Thus, CGD does not have a MEC due to its characteristics.

(c) The particles in a dust cloud must be at a certain distance to enable the flame to propagate from one particle to another.

(d) The distance between the particles should be 450 to 700 μm for the flame to propagate from one particle to another.

(e) The inerts in a dust cloud increases the distance between the combustibles and inhibits the flame propagation.

(f) Approximately 50% of inerts will prevent the flame propagation in an organic dust.

(g) It was observed that the energy content of a dust should be above 7000 J $g^{-1}$ to facilitate a deflagration.

# CHAPTER V

# SUMMARY AND CONCLUSIONS

## Objectives

An alternative explosible dust testing methodology is proposed. The CAAQES explosible dust test method mimics a primary dust explosion by using a stationary source and a diaphragm. According to the CAAQES protocol, a dust is classified as explosible based upon the existence of a MEC. The CAAQES method uses three indicators to determine the MEC of a dust; (a) the pressure rise due to the self-propagating flame must rupture the diaphragm; (b) the self-propagating flame must leave the chamber; and (c) a characteristic Pressure vs. Time curve is obtained. The CAAQES method yields more accurate and reliable results over the current ASTM method. The overall goal was to determine if CGD was explosible. The CAAQES laboratory reported that CGD does not have a MEC, and hence, it is non-explosible. The SCE laboratory reported CGD was a Class „A" explosible dust based on ASTM standard testing procedures. A dust cannot be explosible and non-explosible. Based on the preliminary results we expanded our research on characterizing a dust on explosibility and reported our findings.

### ***Objective 1***

Several flaws were reported on the current ASTM explosible dust testing protocols. The current ASTM method does not use MEC as a criterion to classify a dust as explosible. The only criterion for assuming a deflagration had occurred in the ASTM chamber is pressure rise. Secondly, a moving flame from a 10 kJ igniter is forced through the dust cloud. It is not evident in the ASTM chamber that the flame self-propagates through the dust cloud (Snoeys, Proust, & Going, 2006). Thirdly, the theoretical pressure rise due to a 10 kJ igniter without any dust in a 20-L chamber is 1.4 barg (at STP). Using high ignition energy to ignite the dust cloud yields „over-driven" results leading to classify a dust as explosible when in fact it is not, and finally a 20-L chamber contains only 5.5 grams of oxygen and a complete combustion of 2 grams of dust will consume all the oxygen in the chamber. Thus the ASTM chamber is oxygen-limited. These potential problems in the current ASTM explosible dust test method yields false positive results.

### ***Objective 2***

The objective was to determine if CGD was explosible and determine MECs of several dusts using the CAAQES chamber. The specific objectives were (a) to document the CAAQES explosible dust testing protocols; (b) to demonstrate that a non-spherical chamber can be used without dispersing a dust into the entire chamber to determine MECs; and (c) to compare the MECs determined using the CAAQES chamber with Palmer (1973) and U.S Bureau of Mines. The CAAQES method exactly mimics a primary dust explosion by using a stationary source and a diaphragm. A dust was classified as explosible based upon the existence of a MEC. A deflagration will not occur if the dust concentration is lower than MEC even in the presence of oxygen, ignition source and containment. A pre-test analysis was conducted before testing a dust in the CAAQES chamber. The PSD, particle density, ash content, moisture content and energy content of test dusts were determined to study the dust characteristics. The CAAQES chamber yielded more accurate and reliable results over the ASTM method.

### ***Objective 3***

CGD does not have a MEC and the dust properties rendered it non-explosible. CGD consisted of 87% inerts with a low energy content of 1400 J $g^{-1}$. Several tests were conducted by mixing an inert dust (Fuller‟s earth) with explosible dusts in the CAAQES chamber to demonstrate the impact of inert mass fraction on the explosibility of a dust. The inert mass fraction of corn starch and sugar was increased incrementally by adding Fuller‟s earth. The MECs of admixed dust with different proportion of inerts were determined using the CAAQES chamber. The test results demonstrated that the inert mass fraction inhibits the flame propagation by increasing the MECs of admixed dusts. The combustible particle distance was calculated by assuming uniform dispersion, and all the particles were of same size. It was hypothesized that, at a specific concentration, the combustible particles must be at a certain distance to propagate a flame from one burning particle to another. A theoretical approach was developed to determine the inert percentage required to prevent a deflagration based on combustible particle distance. It was assumed that the inert mass fraction increases the distance between the combustible particles and prevents the flame propagation. The actual inert percentage required to prevent a deflagration was determined using the CAAQES chamber. The dust properties influenced the flame propagation in a dust cloud.

## Conclusions

### *Conclusion 1*

The ASTM chamber cannot be tweaked or altered. A dust must be classified as explosible based on the CAAQES method or a similar protocol used by Palmer (1973) or U.S. Bureau of Mines. A dust must be classified based upon the existence of a MEC. The ASTM method mislabel a dust as explosible, misleading a dust handling facility to install additional control systems at a huge cost without any improvement for worker or public safety.

### *Conclusion 2*

The MECs of several agricultural dusts were determined using the CAAQES chamber. The MECs of corn starch, dust XX, rye flour, brown rice flour, wheat flour, sugar, and rice flour were 25 g $m^{-3}$, 54 g $m^{-3}$, 81 g $m^{-3}$, 72 g $m^{-3}$, 85 g $m^{-3}$, 30 g $m^{-3}$ and 28 g $m^{-3}$, respectively. CGD does not have a MEC and it is non-explosible.

The CAAQES testing protocols ensures the self-propagation of a flame if the dust concentration exceeds the MEC of a dust. Only a fraction of the volume of the chamber was used to determine the MEC of a dust. It was demonstrated that a non-spherical chamber can be used without dispersing the dust into an entire chamber to determine MECs. The MECs determined using the CAAQES chamber were similar to MECs determined by Palmer (1973) and U.S. Bureau of Mines.

### *Conclusion 3*

The inert mass fraction (ash content), PSD, combustible particle distance and energy content influence self-propagation of a flame. The CGD does not have a MEC due to its properties. It consisted of 87% inerts with a low energy content of 1400 J $g^{-1}$. The dust properties of CGD rendered it non-explosible. Approximately 50% of inerts prevented a deflagration for explosible dusts. Palmer (1973) reported that the deflagration was prevented for explosible dusts by increasing the inerts percentage to 60-65%. The effect of ash content (inert mass fraction) on MECs was demonstrated using CS and SG. The inert mass fraction of SG and CS were increased by adding Fuller"s earth. The inert mass fraction affected the self-propagation of a flame. The increase in inert mass fraction increased the MECs of the admixed dusts. The combustible particles must be at a certain distance to facilitate flame propagation. It was demonstrated that the dust properties such as PSD, ash content, energy content and particle density influences the MEC of a dust.

## Future studies

The CAAQES chamber was used to test agricultural dusts for this study. Future studies will be conducted on metal dusts to determine the MECs using the CAAQES chamber.

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# APPENDIX A

# TESTS RESULTS OF EXPLOSIBLE DUSTS IN THE CAAQES CHAMBER

**Table 12.** Test series conducted in the CAAQES chamber to determine MECs **(**Note: The bolded values are the MECs of the corresponding dusts)

| **Dust type** | **Concentration** | **Deflagration** |
|---|---|---|
| | **g m$^{-3}$** | **(Y/N)** |
| CS_100_1 | 100 | Y |
| CS_100_1 | 100 | Y |
| CS_100_1 | 100 | Y |
| CS_90_1 | 90 | Y |
| CS_90_1 | 90 | Y |
| CS_90_1 | 90 | Y |
| CS_75_1 | 75 | Y |
| CS_75_2 | 75 | Y |
| CS_75_3 | 75 | Y |
| CS_60_1 | 60 | Y |
| CS_60_2 | 60 | Y |
| CS_60_3 | 60 | Y |
| CS_50_1 | 50 | Y |
| CS_50_2 | 50 | Y |
| CS_50_3 | 50 | Y |
| CS_45_1 | 45 | Y |
| CS_45_2 | 45 | Y |
| CS_45_3 | 45 | Y |
| CS_40_1 | 40 | Y |
| CS_40_2 | 40 | Y |
| CS_40_3 | 40 | N |
| CS_35_1 | 35 | Y |
| CS_35_2 | 35 | N |
| CS_35_3 | 35 | Y |
| **CS_25_1** | **25** | **Y** |
| **CS_25_2** | **25** | **N** |
| **CS_25_3** | **25** | **N** |
| CS_23_1 | 23 | N |
| CS_23_2 | 23 | N |
| CS_23_3 | 23 | N |
| DUST XX_100_1 | 100 | Y |
| DUST XX_100_2 | 100 | Y |
| DUST XX_100_3 | 100 | Y |
| DUST XX_90_1 | 90 | Y |
| DUST XX_90_2 | 90 | Y |
| DUST XX_90_3 | 90 | Y |
| DUSTXX_80_1 | 80 | Y |

**Table 12**. continued

| **Dust type** | **Concentration**<br>**g m$^{-3}$** | **Deflagration**<br>**(Y/N)** |
|---|---|---|
| DUSTXX_80_2 | 80 | Y |
| DUSTXX_80_3 | 80 | N |
| DUSTXX_57_1 | 57 | N |
| DUSTXX_57_2 | 57 | Y |
| DUSTXX_57_3 | 57 | Y |
| **DUSTXX_54_1** | **54** | **Y** |
| **DUSTXX_54_2** | **54** | **N** |
| **DUSTXX_54_3** | **54** | **N** |
| DUSTXX_50_1 | 50 | N |
| DUSTXX_50_2 | 50 | N |
| DUSTXX_50_3 | 50 | N |
| RF_110_1 | 110 | Y |
| RF_110_2 | 110 | Y |
| RF_110_3 | 110 | Y |
| RF_95_1 | 95 | Y |
| RF_95_2 | 95 | Y |
| RF_95_3 | 95 | Y |
| RF_88_1 | 88 | Y |
| RF_88_2 | 88 | Y |
| RF_88_3 | 88 | Y |
| RF_84_1 | 84 | Y |
| RF_84_2 | 84 | Y |
| RF_84_3 | 84 | N |
| RF_82_1 | 82 | N |
| RF_82_2 | 82 | Y |
| RF_82_3 | 82 | Y |
| **RF_81_1** | **81** | **N** |
| **RF_81_2** | **81** | **Y** |
| **RF_81_3** | **81** | **N** |
| RF_80_1 | 80 | N |
| RF_80_2 | 80 | N |
| RF_80_3 | 80 | N |
| BRF_90_1 | 90 | Y |
| BRF_90_2 | 90 | Y |
| BRF_90_3 | 90 | N |
| BRF_80_1 | 80 | Y |
| BRF_80_2 | 80 | N |
| BRF_80_3 | 80 | N |

**Table 12**. continued

| **Dust type** | **Concentration** | **Deflagration** |
|---|---|---|
| | **g m$^{-3}$** | **(Y/N)** |
| BRF_75_1 | 75 | N |
| BRF_75_2 | 75 | N |
| BRF_75_3 | 75 | Y |
| **BRF_72_1** | **72** | **Y** |
| **BRF_72_2** | **72** | **N** |
| **BRF_72_3** | **72** | **N** |
| BRF_70_1 | 70 | N |
| BRF_70_2 | 70 | N |
| BRF_70_3 | 70 | N |
| WF_100_1 | 100 | Y |
| WF_100_2 | 100 | N |
| WF_100_3 | 100 | Y |
| WF_90_1 | 90 | N |
| WF_90_2 | 90 | Y |
| WF_90_3 | 90 | N |
| **WF_85_1** | **85** | **N** |
| **WF_85_2** | **85** | **N** |
| **WF_85_3** | **85** | **Y** |
| WF_83_1 | 83 | N |
| WF_83_2 | 83 | N |
| WF_83_3 | 83 | N |
| SG_70_1 | 70 | Y |
| SG_70_2 | 70 | Y |
| SG_70_3 | 70 | Y |
| SG_60_1 | 60 | Y |
| SG_60_2 | 60 | Y |
| SG_60_3 | 60 | Y |
| SG_55_1 | 55 | Y |
| SG_55_2 | 55 | Y |
| SG_55_3 | 55 | Y |
| SG_45_1 | 45 | Y |
| SG_45_2 | 45 | N |
| SG_45_3 | 45 | Y |
| SG_40_1 | 40 | Y |
| SG_40_2 | 40 | N |
| SG_40_3 | 40 | Y |
| SG_30_1 | 30 | Y |
| **SG_30_2** | **30** | **N** |

**Table 12**. continued

| **Dust type** | **Concentration** | **Deflagration** |
|---|---|---|
| | **g m$^{-3}$** | **(Y/N)** |
| **SG_30_3** | **30** | **N** |
| **SG_27_1** | **27** | **N** |
| SG_27_2 | 27 | N |
| SG_27_3 | 27 | N |
| RICE_60_1 | 60 | Y |
| RICE_60_2 | 60 | Y |
| RICE_60_3 | 60 | Y |
| RICE_45_1 | 45 | Y |
| RICE_45_2 | 45 | Y |
| RICE_45_3 | 45 | N |
| RICE_40_1 | 40 | Y |
| RICE_40_2 | 40 | N |
| RICE_40_3 | 40 | N |
| **RICE_28_1** | **28** | **Y** |
| **RICE_28_2** | **28** | **N** |
| **RICE_28_3** | **28** | **N** |
| RICE_25_1 | 25 | N |
| RICE_25_2 | 25 | N |
| RICE_25_3 | 25 | N |

# APPENDIX B

# TESTS RESULTS OF INERT PERCENTAGE REQUIRED TO PREVENT A DEFLAGRATION

**Table 13.** Inert percentage required to prevent a deflagration for corn starch

| **Trial** | **Cornstarch** | **Inerts** | **Corn Starch Conc.** | **Inert conc.** | **Total Concentration** | **Inert Percentage** | **Def.** |
|---|---|---|---|---|---|---|---|
| | **(g)** | **(g)** | **g m$^{-3}$** | **g m$^{-3}$** | **g m$^{-3}$** | **%** | |
| 1 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| 2 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| 3 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| | | | | | | | |
| 1 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| 2 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| 3 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| | | | | | | | |
| 1 | 1 | 0.6 | 100 | 60 | 160 | 38 | N |
| 2 | 1 | 0.6 | 100 | 60 | 160 | 38 | N |
| 3 | 1 | 0.6 | 100 | 60 | 160 | 38 | Y |
| | | | | | | | |
| 1 | 1 | 0.65 | 100 | 65 | 165 | 39 | N |
| 2 | 1 | 0.65 | 100 | 65 | 165 | 39 | Y |
| 3 | 1 | 0.65 | 100 | 65 | 165 | 39 | Y |
| | | | | | | | |
| 1 | 1 | 0.7 | 100 | 70 | 170 | 41 | N |
| 2 | 1 | 0.7 | 100 | 70 | 170 | 41 | N |
| 3 | 1 | 0.7 | 100 | 70 | 170 | 41 | Y |
| | | | | | | | |
| 1 | 1 | 0.8 | 100 | 80 | 180 | 44 | N |
| 2 | 1 | 0.8 | 100 | 80 | 180 | 44 | N |
| 3 | 1 | 0.8 | 100 | 80 | 180 | 44 | Y |
| | | | | | | | |
| 1 | 1 | 0.85 | 100 | 85 | 185 | 46 | N |
| 2 | 1 | 0.85 | 100 | 85 | 185 | 46 | N |
| 3 | 1 | 0.85 | 100 | 85 | 185 | 46 | Y |
| | | | | | | | |
| 1 | 1 | 0.89 | 100 | 89 | 189 | 47 | N |
| 2 | 1 | 0.89 | 100 | 89 | 189 | 47 | N |
| 3 | 1 | 0.89 | 100 | 89 | 189 | 47 | N |
| | | | | | | | |
| **1** | **1** | **0.9** | **100** | **90** | **190** | **47** | **N** |
| **2** | **1** | **0.9** | **100** | **90** | **190** | **47** | **N** |
| **3** | **1** | **0.9** | **100** | **90** | **190** | **47** | **N** |

**Table 14.** Inert percentage required to prevent a deflagration for rice flour

| **Trial** | **Rice flour** | **Inerts** | **Rice flour Conc.** | **Inert conc.** | **Total Concentration** | **Inert Percentage** | **Def.** |
|---|---|---|---|---|---|---|---|
| | **(g)** | **(g)** | **g $m^{-3}$** | **g $m^{-3}$** | **g $m^{-3}$** | **%** | |
| 1 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| 2 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| 3 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| | | | | | | | |
| 1 | 1 | 0.6 | 100 | 60 | 160 | 38 | Y |
| 2 | 1 | 0.6 | 100 | 60 | 160 | 38 | N |
| 3 | 1 | 0.6 | 100 | 60 | 160 | 38 | Y |
| | | | | | | | |
| 1 | 1 | 0.65 | 100 | 65 | 165 | 39 | N |
| 2 | 1 | 0.65 | 100 | 65 | 165 | 39 | Y |
| 3 | 1 | 0.65 | 100 | 65 | 165 | 39 | Y |
| | | | | | | | |
| 1 | 1 | 0.7 | 100 | 70 | 170 | 41 | N |
| 2 | 1 | 0.7 | 100 | 70 | 170 | 41 | N |
| 3 | 1 | 0.7 | 100 | 70 | 170 | 41 | Y |
| | | | | | | | |
| 1 | 1 | 0.8 | 100 | 80 | 180 | 44 | N |
| 2 | 1 | 0.8 | 100 | 80 | 180 | 44 | N |
| 3 | 1 | 0.8 | 100 | 80 | 180 | 44 | Y |
| | | | | | | | |
| 1 | 1 | 0.9 | 100 | 90 | 190 | 47 | N |
| 2 | 1 | 0.9 | 100 | 90 | 190 | 47 | N |
| 3 | 1 | 0.9 | 100 | 90 | 190 | 47 | Y |
| | | | | | | | |
| **1** | **1** | **1** | **100** | **100** | **200** | **50** | **N** |
| **2** | **1** | **1** | **100** | **100** | **200** | **50** | **N** |
| **3** | **1** | **1** | **100** | **100** | **200** | **50** | **N** |

**Table 15.** Inert percentage required to prevent a deflagration for sugar

| **Trial** | **Sugar** | **Inerts** | **Sugar Conc.** | **Inert conc.** | **Total Concentration** | **Inert Percentage** | **Def.** |
|---|---|---|---|---|---|---|---|
| | **(g)** | **(g)** | **g m$^{-3}$** | **g m$^{-3}$** | **g m$^{-3}$** | **%** | |
| 1 | 1 | 0.3 | 100 | 30 | 130 | 23 | Y |
| 2 | 1 | 0.3 | 100 | 30 | 130 | 23 | Y |
| 3 | 1 | 0.3 | 100 | 30 | 130 | 23 | Y |
| | | | | | | | |
| 1 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| 2 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| 3 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| | | | | | | | |
| | | | | | | | |
| 1 | 0.7 | 0.3 | 70 | 30 | 100 | 30 | Y |
| 2 | 0.7 | 0.3 | 70 | 30 | 100 | 30 | Y |
| 3 | 0.7 | 0.3 | 70 | 30 | 100 | 30 | Y |
| | | | | | | | |
| 1 | 0.55 | 0.45 | 55 | 45 | 100 | 45 | N |
| 2 | 0.55 | 0.45 | 55 | 45 | 100 | 45 | N |
| 3 | 0.55 | 0.45 | 55 | 45 | 100 | 45 | Y |
| | | | | | | | |
| **1** | **0.53** | **0.47** | **53** | **47** | **100** | **47** | **N** |
| **2** | **0.53** | **0.47** | **53** | **47** | **100** | **47** | **N** |
| **3** | **0.53** | **0.47** | **53** | **47** | **100** | **47** | **N** |

**Table 16.** Inert percentage required to prevent a deflagration for Dust XX

| Trial | Dust XX | Inerts | Dust XX Conc. | Inert conc. | Total Concentration | Inert Percentage | Def. |
|---|---|---|---|---|---|---|---|
| | (g) | (g) | g m$^{-3}$ | g m$^{-3}$ | g m$^{-3}$ | % | |
| 1 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| 2 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| 3 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| | | | | | | | |
| 1 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| 2 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| 3 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| | | | | | | | |
| 1 | 1 | 0.7 | 100 | 70 | 170 | 41 | N |
| 2 | 1 | 0.7 | 100 | 70 | 170 | 41 | N |
| 3 | 1 | 0.7 | 100 | 70 | 170 | 41 | Y |
| | | | | | | | |
| 1 | 1 | 0.8 | 100 | 80 | 180 | 44 | N |
| 2 | 1 | 0.8 | 100 | 80 | 180 | 44 | N |
| 3 | 1 | 0.8 | 100 | 80 | 180 | 44 | Y |
| | | | | | | | |
| 1 | 1 | 0.85 | 100 | 85 | 185 | 46 | N |
| 2 | 1 | 0.85 | 100 | 85 | 185 | 46 | N |
| 3 | 1 | 0.85 | 100 | 85 | 185 | 46 | Y |
| | | | | | | | |
| 1 | 1 | 0.9 | 100 | 90 | 190 | 47 | N |
| 2 | 1 | 0.9 | 100 | 90 | 190 | 47 | N |
| 3 | 1 | 0.9 | 100 | 90 | 190 | 47 | Y |
| | | | | | | | |
| **1** | **1** | **0.95** | **100** | **95** | **195** | **48** | **N** |
| **2** | **1** | **0.95** | **100** | **95** | **195** | **48** | **N** |
| **3** | **1** | **0.95** | **100** | **95** | **195** | **48** | **N** |

**Table 17.** Inert percentage required to prevent a deflagration for rye flour

| Trial | Rye flour | Inerts | Rye flour Conc. | Inert conc. | Total Concentration | Inert Percentage | Def. |
|---|---|---|---|---|---|---|---|
| | **(g)** | **(g)** | **g m$^{-3}$** | **g m$^{-3}$** | **g m$^{-3}$** | **%** | |
| 1 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| 2 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| 3 | 1 | 0.4 | 100 | 40 | 140 | 29 | Y |
| | | | | | | | |
| 1 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| 2 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| 3 | 1 | 0.5 | 100 | 50 | 150 | 33 | Y |
| | | | | | | | |
| 1 | 1 | 0.65 | 100 | 65 | 165 | 39 | Y |
| 2 | 1 | 0.65 | 100 | 65 | 165 | 39 | N |
| 3 | 1 | 0.65 | 100 | 65 | 165 | 39 | Y |
| | | | | | | | |
| 1 | 1 | 0.8 | 100 | 80 | 180 | 44 | N |
| 2 | 1 | 0.8 | 100 | 80 | 180 | 44 | Y |
| 3 | 1 | 0.8 | 100 | 80 | 180 | 44 | Y |
| | | | | | | | |
| 1 | 1 | 0.95 | 100 | 95 | 195 | 49 | N |
| 2 | 1 | 0.95 | 100 | 95 | 195 | 49 | N |
| 3 | 1 | 0.95 | 100 | 95 | 195 | 49 | Y |
| | | | | | | | |
| **1** | **1** | **0.98** | **100** | **98** | **198** | **49** | **N** |
| **2** | **1** | **0.98** | **100** | **98** | **198** | **49** | **N** |
| **3** | **1** | **0.98** | **100** | **98** | **198** | **49** | **N** |

**Table 18.** Inert percentage required to prevent a deflagration for brown rice flour

| Trial | Brown rice | Inerts | Brown rice Conc. | Inert conc. | Total Concentration | Inert Percentage | Def. |
|---|---|---|---|---|---|---|---|
| | (g) | (g) | g $m^{-3}$ | g $m^{-3}$ | g $m^{-3}$ | % | |
| 1 | 1 | 0.55 | 100 | 55 | 155 | 35 | Y |
| 2 | 1 | 0.55 | 100 | 55 | 155 | 35 | Y |
| 3 | 1 | 0.55 | 100 | 55 | 155 | 35 | Y |
| | | | | | | | |
| 1 | 1 | 0.6 | 100 | 60 | 160 | 38 | Y |
| 2 | 1 | 0.6 | 100 | 60 | 160 | 38 | Y |
| 3 | 1 | 0.6 | 100 | 60 | 160 | 38 | Y |
| | | | | | | | |
| 1 | 1 | 0.75 | 100 | 75 | 175 | 43 | N |
| 2 | 1 | 0.75 | 100 | 75 | 175 | 43 | N |
| 3 | 1 | 0.75 | 100 | 75 | 175 | 43 | Y |
| | | | | | | | |
| 1 | 1 | 0.85 | 100 | 85 | 185 | 46 | N |
| 2 | 1 | 0.85 | 100 | 85 | 185 | 46 | N |
| 3 | 1 | 0.85 | 100 | 85 | 185 | 46 | Y |
| | | | | | | | |
| 1 | 1 | 0.87 | 100 | 87 | 187 | 47 | Y |
| 2 | 1 | 0.87 | 100 | 87 | 187 | 47 | N |
| 3 | 1 | 0.87 | 100 | 87 | 187 | 47 | N |
| | | | | | | | |
| **1** | **1** | **0.9** | **100** | **90** | **190** | **47** | **N** |
| **2** | **1** | **0.9** | **100** | **90** | **190** | **47** | **N** |
| **3** | **1** | **0.9** | **100** | **90** | **190** | **47** | **N** |

**Table 19.** Inert percentage required to prevent a deflagration for wheat flour

| Trial | Wheat flour | Inerts | Wheat flour Conc. | Inert conc. | Total Concentration | Inert Percentage | Def. |
|---|---|---|---|---|---|---|---|
| | **(g)** | **(g)** | **g m$^{-3}$** | **g m$^{-3}$** | **g m$^{-3}$** | **%** | |
| 1 | 1.2 | 0.55 | 120 | 55 | 175 | 31 | Y |
| 2 | 1.2 | 0.55 | 120 | 55 | 175 | 31 | Y |
| 3 | 1.2 | 0.55 | 120 | 55 | 175 | 31 | Y |
| | | | | | | | |
| 1 | 1.2 | 0.65 | 120 | 65 | 185 | 35 | Y |
| 2 | 1.2 | 0.65 | 120 | 65 | 185 | 35 | Y |
| 3 | 1.2 | 0.65 | 120 | 65 | 185 | 35 | Y |
| | | | | | | | |
| 1 | 1.2 | 0.7 | 120 | 70 | 190 | 37 | Y |
| 2 | 1.2 | 0.7 | 120 | 70 | 190 | 37 | N |
| 3 | 1.2 | 0.7 | 120 | 70 | 190 | 37 | N |
| | | | | | | | |
| 1 | 1.2 | 0.9 | 120 | 90 | 210 | 43 | N |
| 2 | 1.2 | 0.9 | 120 | 90 | 210 | 43 | N |
| 3 | 1.2 | 0.9 | 120 | 90 | 210 | 43 | N |
| | | | | | | | |
| **1** | **1.2** | **0.8** | **120** | **80** | **200** | **40** | **N** |
| **2** | **1.2** | **0.8** | **120** | **80** | **200** | **40** | **N** |
| **3** | **1.2** | **0.8** | **120** | **80** | **200** | **40** | **N** |
| | | | | | | | |
| 1 | 1.2 | 0.76 | 120 | 76 | 196 | 39 | N |
| 2 | 1.2 | 0.76 | 120 | 76 | 196 | 39 | N |
| 3 | 1.2 | 0.76 | 120 | 76 | 196 | 39 | Y |

# APPENDIX C

## MECs OF ADMIXED DUSTS DETERMINED USING THE CAAQES CHAMBER FOR DIFFERENT INERT PERCENTAGE

**Table 20.** MECs of admixed dusts for different proportions of inert percentage determined using the CAAQES chamber

| **Trial** | **Corn Starch Conc.** | **Inert conc.** | **Total Concentration** | **Inert Percentage** | **Def.** |
|---|---|---|---|---|---|
| | **g m$^{-3}$** | **g m$^{-3}$** | **g m$^{-3}$** | **%** | |
| 1 | 47.5 | 2.5 | 50 | 5 | Y |
| 2 | 47.5 | 2.5 | 50 | 5 | Y |
| 3 | 47.5 | 2.5 | 50 | 5 | Y |
| | | | | | |
| 1 | 28.5 | 1.5 | 30 | 5 | N |
| 2 | 28.5 | 1.5 | 30 | 5 | N |
| 3 | 28.5 | 1.5 | 30 | 5 | Y |
| | | | | | |
| **1** | **23.75** | **1.25** | **25** | **5** | **Y** |
| **2** | **23.75** | **1.25** | **25** | **5** | **N** |
| **3** | **23.75** | **1.25** | **25** | **5** | **Y** |
| | | | | | |
| 1 | 45 | 5 | 50 | 10 | Y |
| 2 | 45 | 5 | 50 | 10 | Y |
| 3 | 45 | 5 | 50 | 10 | Y |
| | | | | | |
| 1 | 22.5 | 2.5 | 25 | 10 | N |
| 2 | 22.5 | 2.5 | 25 | 10 | N |
| 3 | 22.5 | 2.5 | 25 | 10 | N |
| | | | | | |
| 1 | 27 | 3 | 30 | 10 | N |
| 2 | 27 | 3 | 30 | 10 | N |
| 3 | 27 | 3 | 30 | 10 | N |
| | | | | | |
| **1** | **31.5** | **3.5** | **35** | **10** | **N** |
| **2** | **31.5** | **3.5** | **35** | **10** | **N** |
| **3** | **31.5** | **3.5** | **35** | **10** | **Y** |
| | | | | | |
| 1 | 42.5 | 7.5 | 50 | 15 | Y |
| 2 | 42.5 | 7.5 | 50 | 15 | Y |
| 3 | 42.5 | 7.5 | 50 | 15 | Y |
| | | | | | |
| **1** | **36** | **4** | **40** | **15** | **Y** |
| **2** | **36** | **4** | **40** | **15** | **N** |
| **3** | **36** | **4** | **40** | **15** | **N** |

**Table 20**. continued

| Trial | Corn Starch Conc. | Inert conc. | Total Concentration | Inert Percentage | Def. |
|---|---|---|---|---|---|
| | g m$^{-3}$ | g m$^{-3}$ | g m$^{-3}$ | % | |
| 1 | 44 | 11 | 55 | 20 | N |
| 2 | 44 | 11 | 55 | 20 | Y |
| 3 | 44 | 11 | 55 | 20 | N |
| | | | | | |
| **1** | **40** | **10** | **50** | **20** | **N** |
| **2** | **40** | **10** | **50** | **20** | **Y** |
| **3** | **40** | **10** | **50** | **20** | **N** |
| | | | | | |
| 1 | 36 | 9 | 45 | 20 | N |
| 2 | 36 | 9 | 45 | 20 | N |
| 3 | 36 | 9 | 45 | 20 | N |
| | | | | | |
| 1 | 45 | 15 | 60 | 25 | N |
| 2 | 45 | 15 | 60 | 25 | N |
| 3 | 45 | 15 | 60 | 25 | Y |
| | | | | | |
| **1** | **52.5** | **17.5** | **70** | **25** | **N** |
| **2** | **52.5** | **17.5** | **70** | **25** | **N** |
| **3** | **52.5** | **17.5** | **70** | **25** | **Y** |
| | | | | | |
| 1 | 63 | 27 | 90 | 30 | N |
| 2 | 63 | 27 | 90 | 30 | Y |
| 3 | 63 | 27 | 90 | 30 | N |
| | | | | | |
| **1** | **56** | **24** | **80** | **30** | **N** |
| **2** | **56** | **24** | **80** | **30** | **N** |
| **3** | **56** | **24** | **80** | **30** | **Y** |
| | | | | | |
| 1 | 49 | 21 | 70 | 30 | N |
| 2 | 49 | 21 | 70 | 30 | N |
| 3 | 49 | 21 | 70 | 30 | N |
| | | | | | |
| 1 | 65 | 35 | 100 | 35 | N |

**Table 20**. continued

| **Trial** | **Corn Starch Conc.** | **Inert conc.** | **Total Concentration** | **Inert Percentage** | **Def.** |
|---|---|---|---|---|---|
| | **g m$^{-3}$** | **g m$^{-3}$** | **g m$^{-3}$** | **%** | |
| 2 | 65 | 35 | 100 | 35 | N |
| 3 | 65 | 35 | 100 | 35 | N |
| | | | | | |
| 1 | 71.5 | 38.5 | 110 | 35 | Y |
| 2 | 71.5 | 38.5 | 110 | 35 | N |
| 3 | 71.5 | 38.5 | 110 | 35 | Y |
| | | | | | |
| **1** | **68.25** | **36.75** | **105** | **35** | **Y** |
| **2** | **68.25** | **36.75** | **105** | **35** | **N** |
| **3** | **68.25** | **36.75** | **105** | **35** | **N** |
| | | | | | |
| 1 | 72 | 48 | 120 | 40 | N |
| 2 | 72 | 48 | 120 | 40 | N |
| 3 | 72 | 48 | 120 | 40 | N |
| | | | | | |
| 1 | 78 | 52 | 130 | 40 | N |
| 2 | 78 | 52 | 130 | 40 | N |
| 3 | 78 | 52 | 130 | 40 | N |
| | | | | | |
| **1** | **84** | **56** | **140** | **40** | **N** |
| **2** | **84** | **56** | **140** | **40** | **Y** |
| **3** | **84** | **56** | **140** | **40** | **N** |
| | | | | | |

# APPENDIX D

# DESIGN OF EXPERIMENT

**Table 21.** Pressure rise in the CAAQES chamber for corn starch for different factors

| **Standard order** | **Blast time** | **Ignition Time** | **Pressure** | **Concentration** | **Particle size** | **Response Pressure Rise** |
|---|---|---|---|---|---|---|
| **Units** | **(s)** | **(mins)** | **(psig)** | **(g/m$^3$)** | **μm** | **(psig)** |
| | **A** | **B** | **C** | **D** | **E=ABCD** | |
| 1 | 1.5 | 2 | 20 | 40 | 150 | 0.35 |
| 2 | 3 | 2 | 20 | 40 | 75 | 1.64 |
| 3 | 1.5 | 4 | 20 | 40 | 75 | 1.53 |
| 4 | 3 | 4 | 20 | 40 | 150 | 1.45 |
| 5 | 1.5 | 2 | 40 | 40 | 75 | 1.6 |
| 6 | 3 | 2 | 40 | 40 | 150 | 1.89 |
| 7 | 1.5 | 4 | 40 | 40 | 150 | 1.77 |
| 8 | 3 | 4 | 40 | 40 | 75 | 1.59 |
| 9 | 1.5 | 2 | 20 | 80 | 75 | 1.22 |
| 10 | 3 | 2 | 20 | 80 | 150 | 0.69 |
| 11 | 1.5 | 4 | 20 | 80 | 150 | 1.51 |
| 12 | 3 | 4 | 20 | 80 | 75 | 0.55 |
| 13 | 1.5 | 2 | 40 | 80 | 150 | 1.59 |
| 14 | 3 | 2 | 40 | 80 | 75 | 1.61 |
| 15 | 1.5 | 4 | 40 | 80 | 75 | 1.42 |
| 16 | 3 | 4 | 40 | 80 | 150 | 0.55 |

**Table 22.** ANOVA output obtained using Design Expert for $2^5$-half fraction factorial experiment

| ANOVA for selected factorial model | | | | | | |
|---|---|---|---|---|---|---|
| Analysis of variance table [Partial sum of squares - Type III] | | | | | | |
| | Sum of | | Mean | F | p-value | |
| Source | Squares | df | Square | Value | Prob > F | |
| Model | 3.61305 | 10 | 0.361305 | 26.04938717 | 0.0011 | significant |
| A-Blast time | 0.075625 | 1 | 0.075625 | 5.452415285 | 0.0668 | |
| B-Ignition coil time | 0.001225 | 1 | 0.001225 | 0.088320115 | 0.7783 | |
| C-Pressure | 0.6241 | 1 | 0.6241 | 44.9963951 | 0.0011 | |
| D-Concentration | 0.4761 | 1 | 0.4761 | 34.3258832 | 0.0021 | |
| E-Particle size | 0.1296 | 1 | 0.1296 | 9.343907714 | 0.0282 | |
| AB | 0.5929 | 1 | 0.5929 | 42.74693583 | 0.0013 | |
| AD | 0.874225 | 1 | 0.874225 | 63.02992069 | 0.0005 | |
| BC | 0.416025 | 1 | 0.416025 | 29.99459265 | 0.0028 | |
| BD | 0.216225 | 1 | 0.216225 | 15.58940159 | 0.0109 | |
| BE | 0.207025 | 1 | 0.207025 | 14.9260995 | 0.0118 | |
| Residual | 0.06935 | 5 | 0.01387 | | | |
| Cor Total | 3.6824 | 15 | | | | |

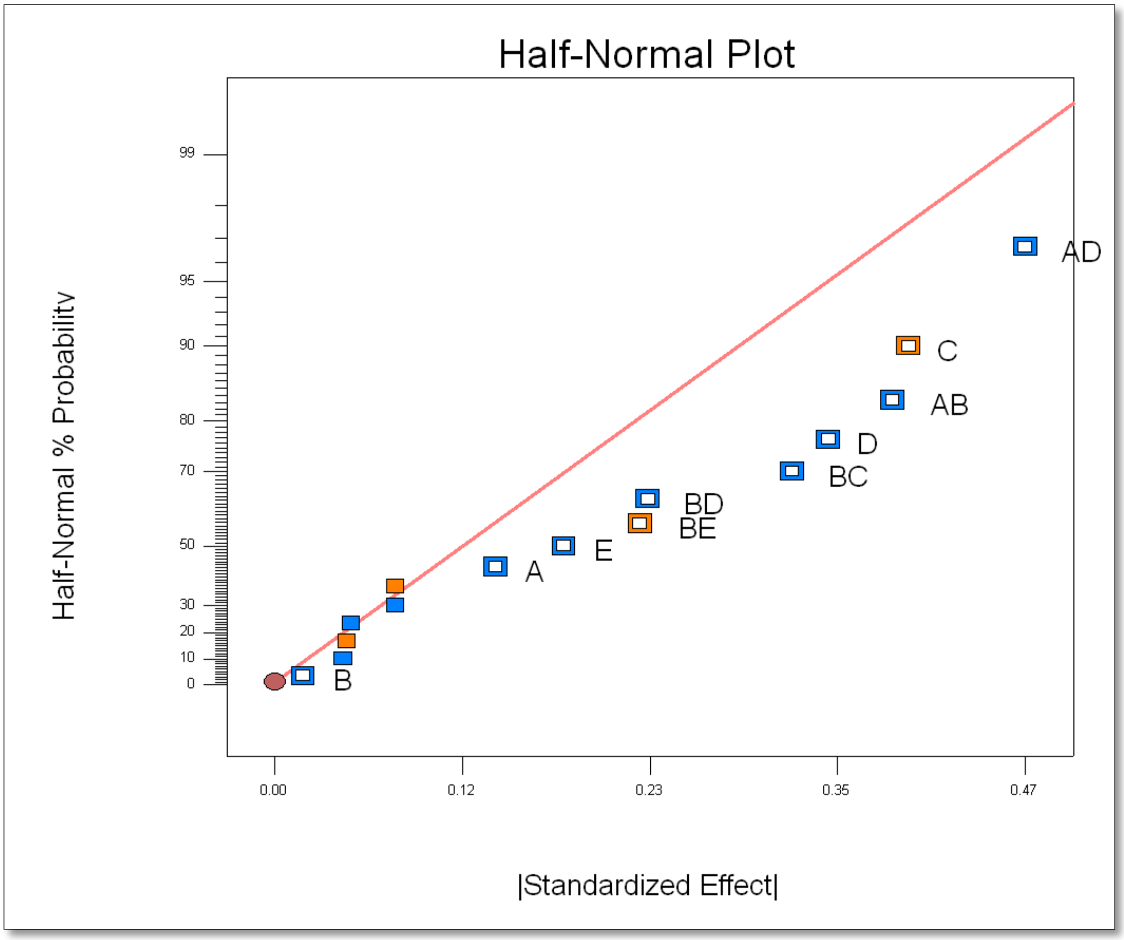

**Figure 26.** Half-normal plots obtained for the model using Design Expert

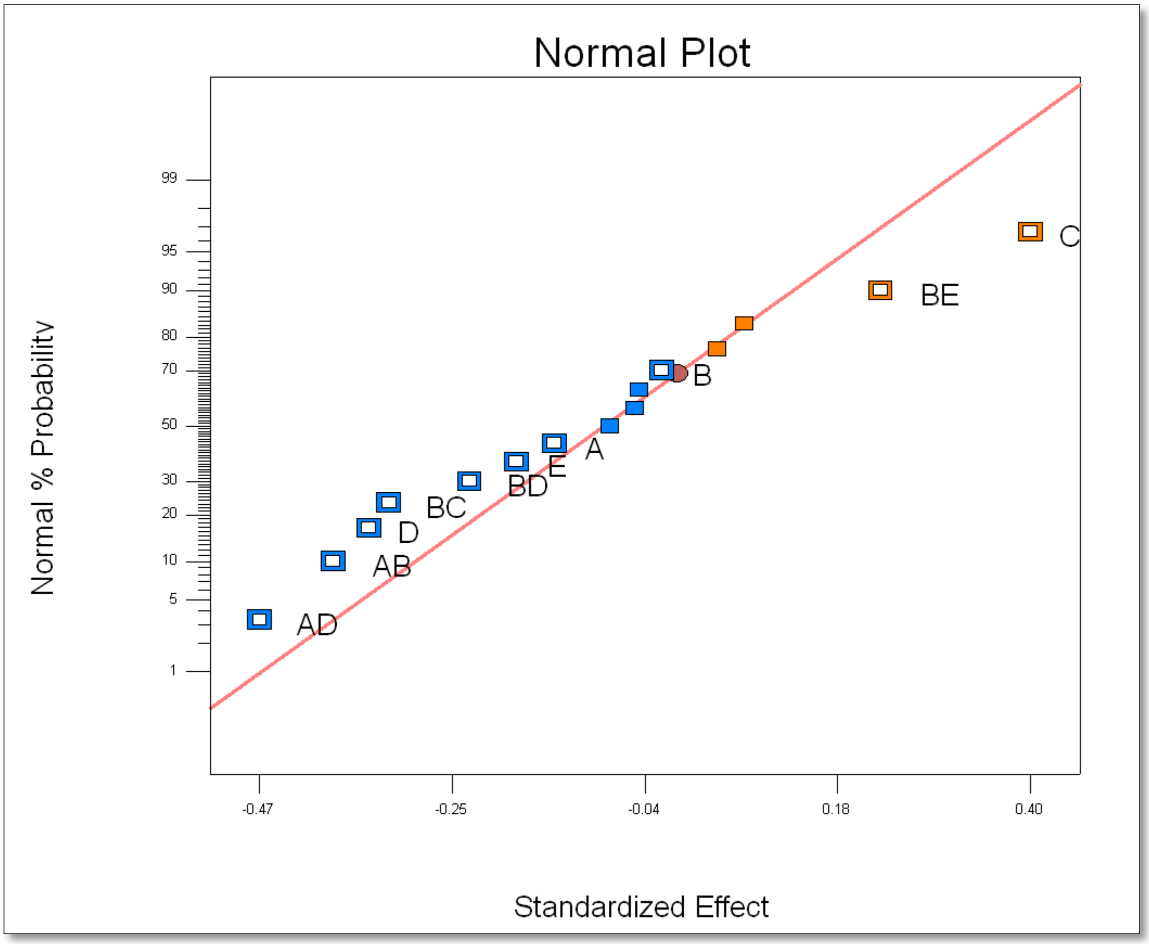

**Figure 27.** Normal plots for the model obtained using Design Expert

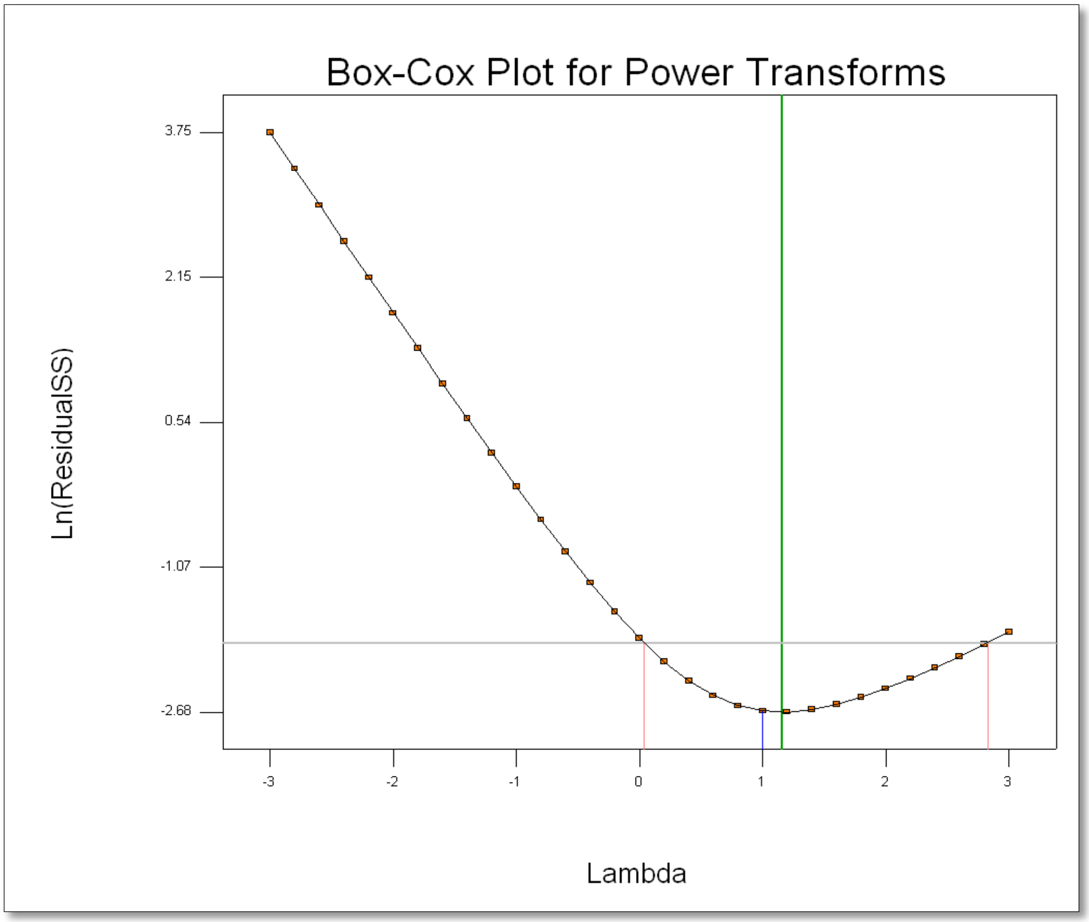

**Figure 28.** Box-Cox plot for the model obtained using Design Expert

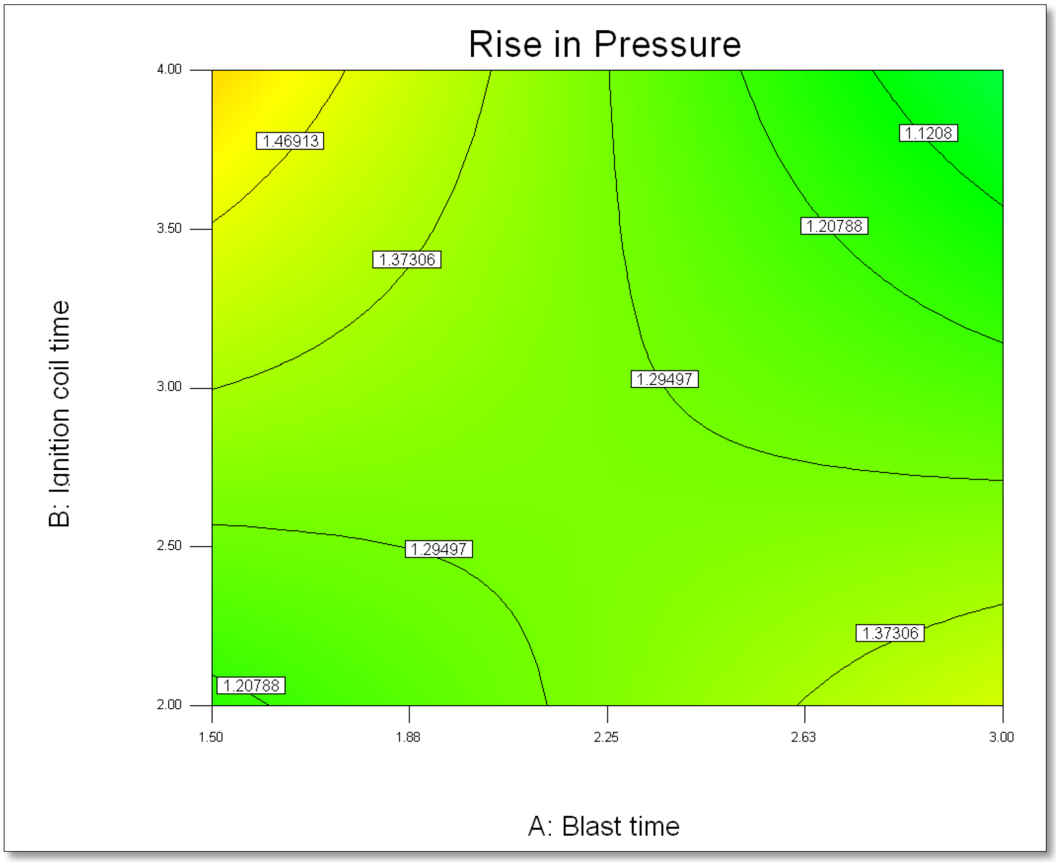

**Figure 29.** Rise in pressure in the CAAQES Chamber due to factors blast time and ignition coil time

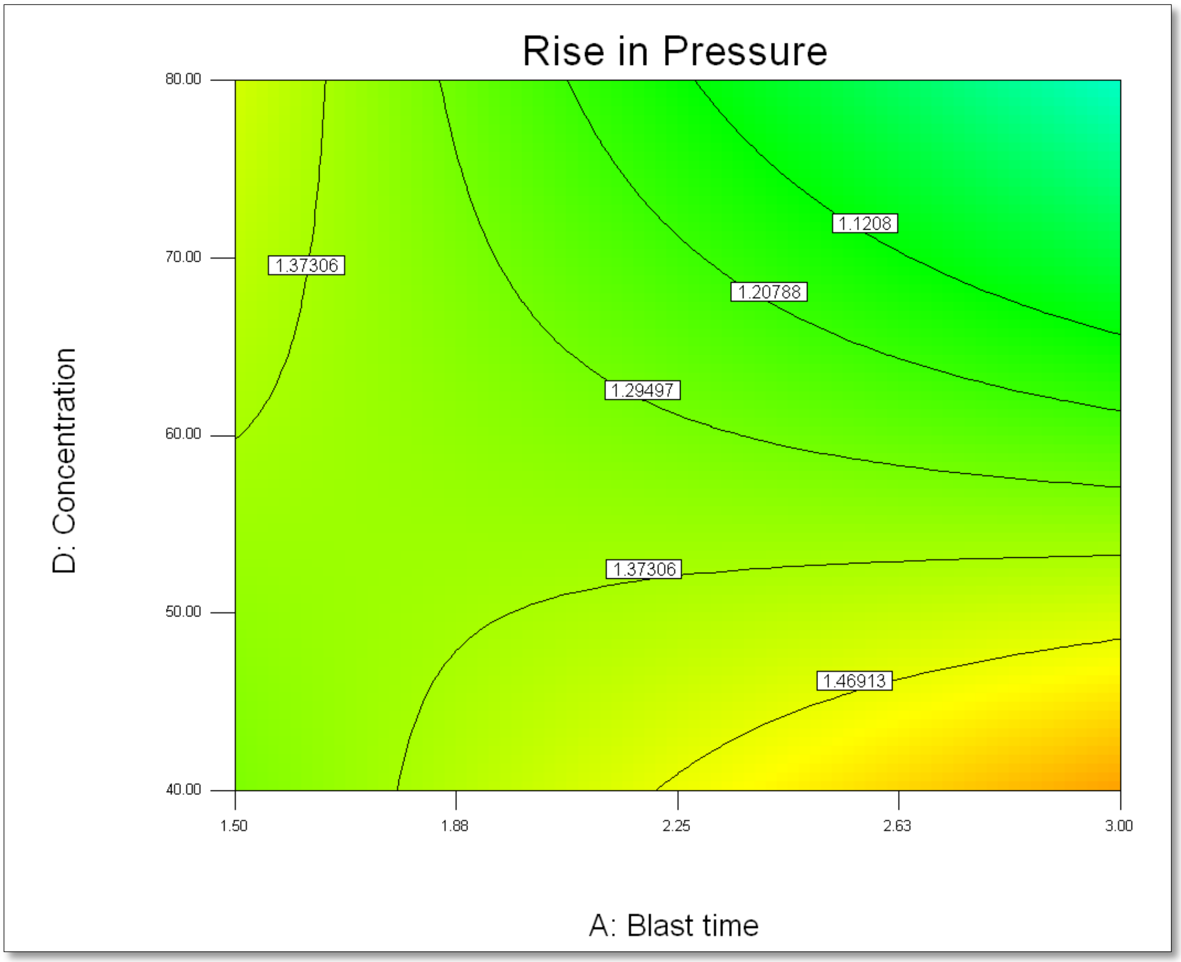

**Figure 30.** Pressure rise in the CAAQES chamber due to factors blast time and concentration

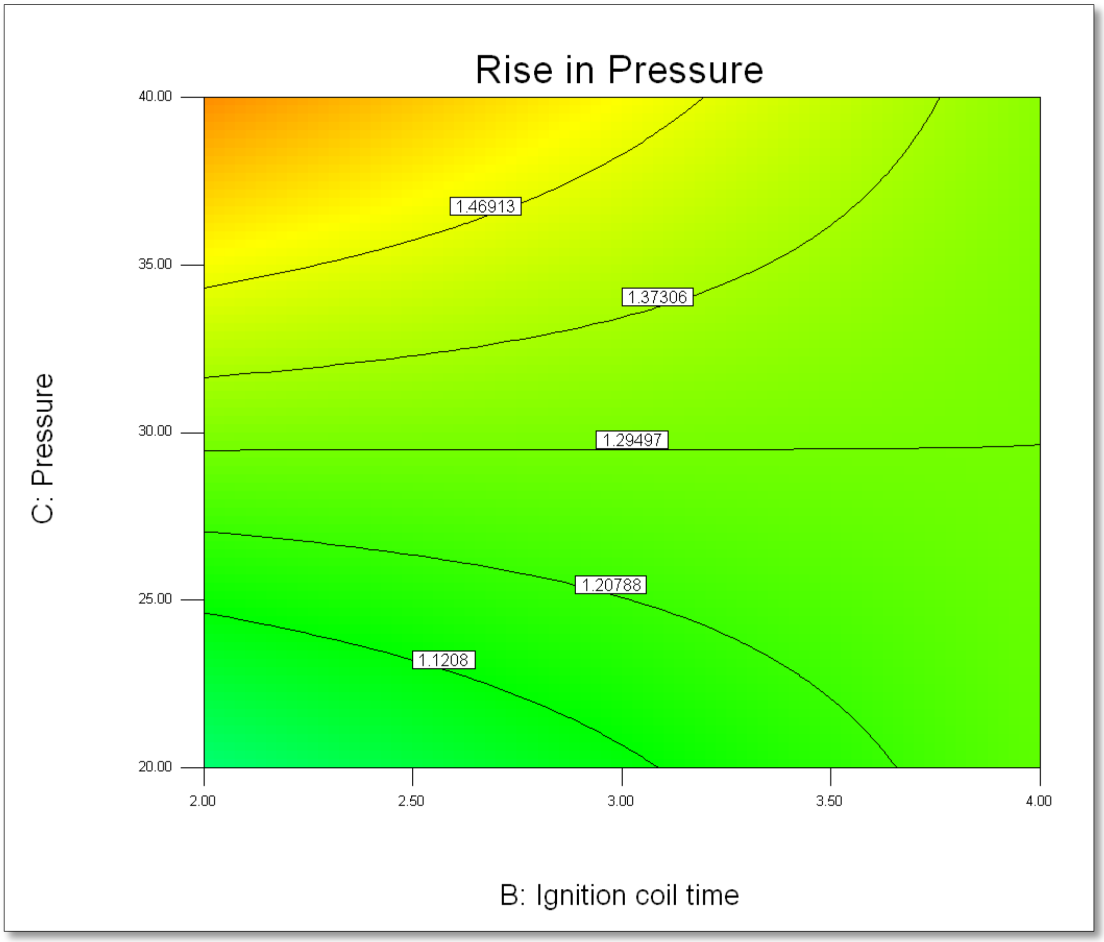

**Figure 31.** Pressure rise in the CAAQES chamber due to factors compressed air pressure and ignition coil time

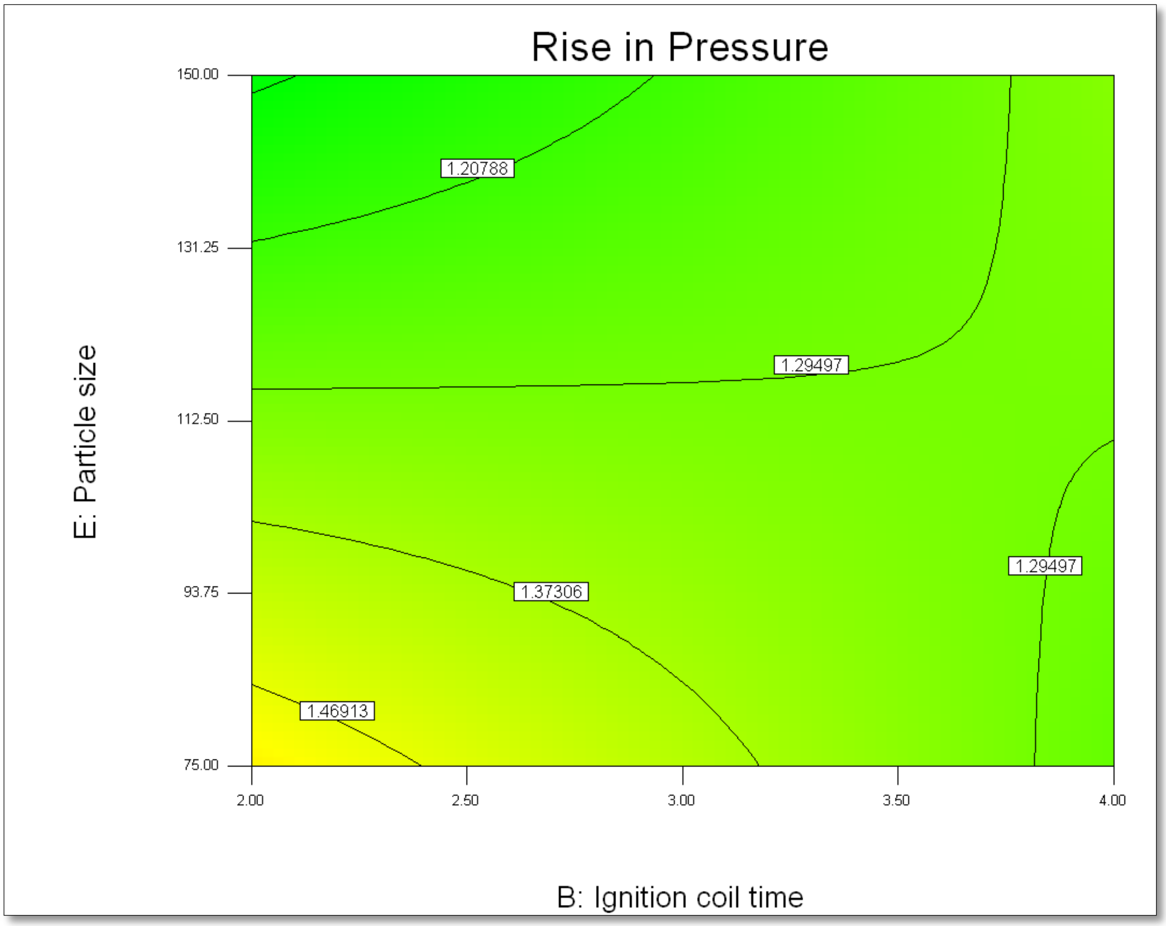

**Figure 32.** Pressure rise in the CAAQES chamber due to factors particle size and ignition coil time